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March 1987

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SIMULATION MODEL OF A PWR PLANT

Niels Larsen

Abstract. A simulation model of a hypothetical PWR power plant is described. A large number of disturbances and failures in plant function can be simulated. The model is written as seven modules to the modular simulation system for continuous processes DYSIM and serves also as a user example of this system. The model runs in Fortran 77 on the IBM-PC-AT.

March 1987
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1. INTRODUCTION

A simulation model of a hypothetical PWR power plant has been constructed.

The model was intended to be used in a study of psychological optimal display systems, i.e. systems used by plant operators to get an overview of the state of a complicated power plant. Because one wants to investigate how operators react in critical situations using the display systems, the model has been provided with a large number of possible disturbances and failures in plant function, which the user can generate. Further the model behaviour should be reasonably realistic when used against trained operators. On the other hand many simplifications have been made to limit the computer code to a manageable size, partly because the model should run on a smaller personal computer.

Secondly, the model illustrates many of the features of DYSIM, the simulation system for continuous processes, developed at the Department of Energy Technology, Risø National Laboratory.

The diagram of the PWR power plant is found in Fig. 1.1. It consists of the reactor with control rods and the pressurizer system, the steam generator, and the steam load system. Water heated in the reactor is led through the U-tube of the steam generator. Steam from the steam generator drives the HP-turbine. The HP-turbine outlet flow is superheated before it is sent to the LP-turbine. The LP-turbine outlet steam is condensed in the condenser which is cooled with seawater. Extraction flows from the turbines preheat the feedwater before it enters the steam generator. Steam is dumped directly to the condenser at high steam line pressure. Relief - and safety valves are present on both sides. Two minor lubrication oil systems are attached to the primary coolant pump and the feedwater pump. Eight controller systems are present besides the reactor - and the turbine trip systems.

The model is divided into seven modules to be connected to the general simulation system DYSIM. Several technical standard components of the plant have been described as submodules. The submodules together with some standard functions constitute a library which is used when constructing the modules.

In the following sections 2-9 the mathematical description of the modules are given together with controller actions and possible disturbances or failures. Section 10 describes the simulation system, gives a detailed list of all possible transients and explains how to use the simulation model. Section 11 gives an example of a transient. Physical data and steady state values for all modules are found in appendix A1-A9. Appendix B holds the list file used by the simulation system. Appendix C gives an example of an input file. It is advised to consult section 10 before the model is used on the computer.

The model runs and has been tested on an IBM personal computer AT 3, equipped with 640 Kbytes memory, hard disk, and floating point co-processor under DOS 3.20 operating system. The modules are written in standard fortran 77, and the model in connection with the DYSIM simulation system has been compiled with the Lahey fortran 77 compiler. An identical version of the model runs on the Risø mainframe Burroughs B7800.

The physical data used in the model originate from the Ringhals 3 power plant simulator (cf. Christensen 1981). In that model one reactor drives three steam generators which in turn drives two turbine sections. In the present model one turbine section of the Ringhals plant is simulated, corresponding to 3/2 steam generator power and 1/2 reactor power. However, the calculations internally in the modules are performed for one turbine section, one steam generator and one reactor and the output data are scaled thereafter (1, 3/2, and 1/2, respectively).

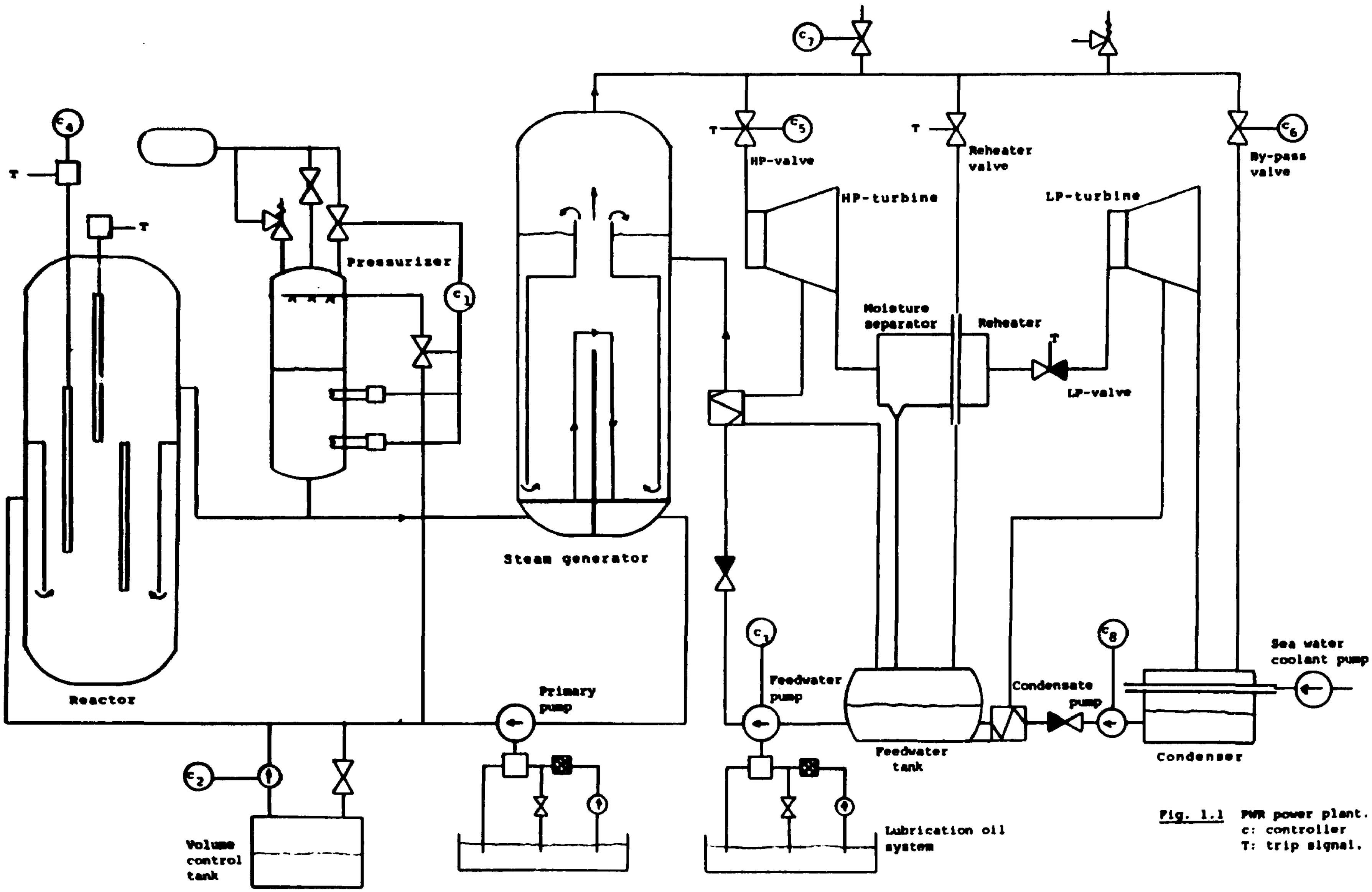


Fig. 1.1 PWR power plant.
c: controller
T: trip signal.

2. REACTOR

The reactor module is shown in Fig. 2.1. It consists of the reactor tank with control rod mechanisms, connection tubes to the steam generator (hot and cold leg), and the primary pump with the attached lubrication oil system (described in section 8).

2.1. Nuclear power

The nuclear energy production is calculated very simplified from a point model. Control rods for adjusting the power have been lumped into one rod. This rod is moved by the controlled motor. The relative control rod position CR is measured from the bottom of the core region (cf. Fig. 2.1), i.e. CR = 0 ~ rod in; CR = 1 ~ rod out. Another rod, the scram rod is used for a fast turn-down of the reactor in case of a trip situation. This rod is released by the scram mechanism. Under normal conditions the rod is out of the reactor and not used for power control.

The nuclear power is calculated from the kinetics equation for the density of delayed neutrons n (cf. Ash 1965, eq. 1.25 and 1.26).

$$\frac{dn}{dt} = \frac{(1-\beta)k_{eff}-1}{l}\, n(t) + \sum_{i=1}^{3} \lambda_i c_i(t) \qquad (2.1)$$

$$\frac{dc_i}{dt} = -\lambda_i c_i(t) + \frac{\beta_i k_{eff}}{l}\, n(t); \quad i = 1,2,3 \qquad (2.2)$$

For simplicity only three delayed neutron groups are used where c_i gives the concentration of the i'th group of delayed neutron precursors, β_i the fractional yield of delayed neutrons per fission neutron and λ_i the decay constant of the delayed neutron emitter of the i'th group. β is the overall fractional yield, k_{eff} is the effective reproduction factor and l is the prompt neutron lifetime.

Assuming that the neutron dynamics is so fast that the neutron density reaches a state of equilibrium for each integration step means that dn/dt = 0 in eq. (2.1) which gives

$$n(t) = \frac{-l\Sigma\lambda_i c_i}{(1-\beta)k_{eff}-1} \tag{2.3}$$

Furthermore the nuclear power Q_{nucl} is assumed proportional to the neutron density

$$\begin{aligned} Q_{nucl}(t) &= pn(t) \\ &= \frac{-l\Sigma\lambda_i pc_i}{(1-\beta)k_{eff}-1} \\ &= \frac{-l\Sigma\lambda_i \gamma_i}{(1-\beta)k_{eff}-1} \end{aligned} \tag{2.4}$$

where

$$\gamma_i = pc_i; \quad i = 1,2,3$$

Equation (2.2) is multiplied by p to give

$$\frac{d(\gamma_i)}{dt} = -\lambda_i\gamma_i(t) + \frac{\beta_i k_{eff}}{l} Q_{nucl}(t); \; i = 1,2,3 \tag{2.5}$$

that is the nuclear power is calculated using (2.4) and (2.5). Assuming an unscaled steady state value of $Q_{nucl}(o) = Q_{norm}$, the initial values (steady state) of γ_i, i = 1,2,3 are calculated from (2.5) using

$$\frac{d\gamma_i}{dt} = 0,$$

as

$$\gamma_i(0) = \frac{\beta_i k_{eff}}{l\lambda_i} Q_{norm}; \quad i = 1,2,3 \tag{2.6}$$

where k_{eff} = 1 in steady state.
The effective reproduction factor k_{eff} is calculated as

$$k_{eff} = 1+DR_{TU}+DR_{TC}+DR_{CR} \tag{2.7}$$

where DR_{TU}, DR_{TC}, and DR_{CR} are reactivity coefficients due to fuel temperature T_U, moderator temperature (i.e. coolant core temperature) T_C and control rod position CR respectively. These coefficients are given from

$$\begin{aligned} DR_{TU} &= C_{TU}(T_U - T_{Unorm}) \\ DR_{TC} &= C_{TC}(T_{avg} - T_{Cnorm}) \\ DR_{CR} &= C_{CR}(CR - 0.5) \end{aligned} \tag{2.8}$$

using the average coolant temperature in the core T_{avg}.

2.2. Primary loop

The primary coolant loop is divided into 8 sections (cf. Fig. 2.1): The reactor inlet chamber, reactor lower plenum, reactor core, reactor upper plenum, hot leg, connecting tube, primary pump chamber, and cold leg. Water temperatures of these regions are indicated on Fig. 2.1.

The reactor average core coolant temperature T_{avg} is calculated from the inlet temperature T_{1p} and outlet temperature T_C by a standard routine. For further details see appendix D.

The heat transfer from fuel to coolant is given from

$$Q_{trans} = H(T_U - T_{avg}) \tag{2.9}$$

where H is the heat transfer coefficient. The fuel temperature T_U is calculated from

$$C_{fuel} \frac{dT_U}{dt} = Q_{nucl} - Q_{trans} \tag{2.10}$$

where C_{fuel} is the total fuel heat capacity. Energy balance then also gives the core coolant temperature T_C

$$c_p \rho_{fc} V_c \frac{dT_C}{dt} = Q_{trans} + c_p W_p (T_{1p} - T_C) \tag{2.11}$$

where c_p, ρ_{fc}, V_c, and W_p are specific heat capacity and density of coolant, volume of core and coolant mass flow respectively.

Temperatures of coolant in the other loop sections are calculated from energy balance in the same way, e.g. the hot leg:

$$\rho_{hl} V_{hl} \frac{dT_{hl}}{dt} = W_p (T_{up} - T_{hl}) \tag{2.12}$$

where ρ, V, and W_p are density, volume, and flow of the section respectively.

The primary flow, W_p, is for simplicity set proportional to the primary pump speed, SP_{pp}

$$W_p = SP_{pp} W_{pnorm} \tag{2.13}$$

2.3. Reactor trip and failures

In case of a reactor trip, indicated by a non-zero trip signal from the controller module (cf. section 9), eq. (2.4) is not used. Instead nuclear power is maintained at its value for 0.3 seconds and then decreased lineary within 0.3 seconds to 5% of the previous value.

When a reactor trip occurs the scram rod is released and nuclear power is decreased as described above. However, if the scram mechanism is not working (switch turned off, cf. section 10 for possible failures) the scram rod does not fall in and nuclear power is still given by the control rod position according to eq. (2.3). In a trip situation the control rod is moved into the reactor at maximum speed. If the control rod motor switch is turned off, the control rod remains in the fixed position when the switch was turned off.

The part of the primary circuit within the steam generator is described in section 5.

If the primary pump motor fails, indicated by a stop signal from the lubrication oil system (cf. section 8), the flow decreases exponentially with a time constant of 10 seconds.

All physical constants and steady state values for this module are found in appendix A2.

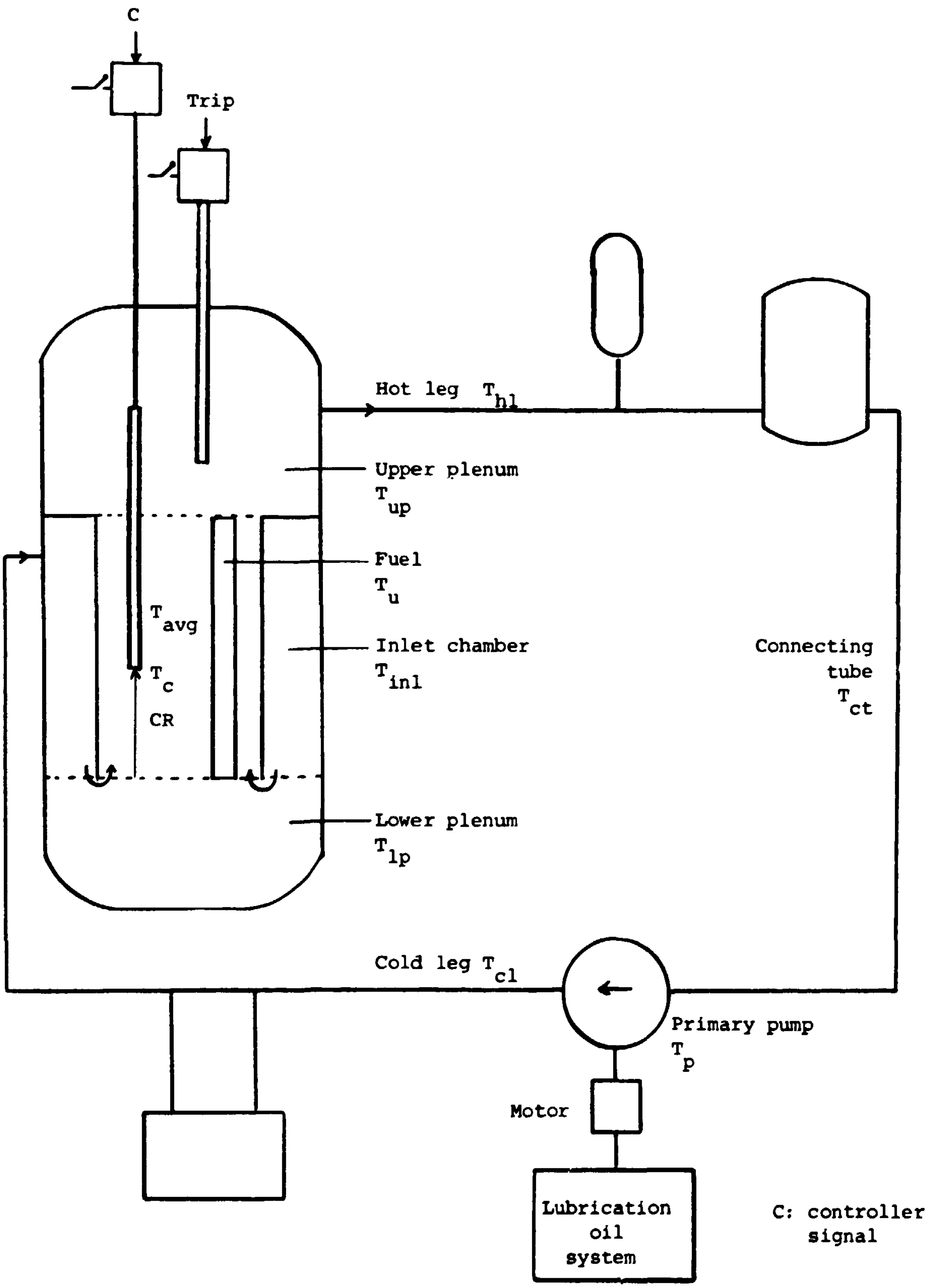


Fig. 2.1 Reactor and primary loop.

3. PRESSURIZER

The pressurizer module consists of the pressurizer tank with the attached heating and spray cooling system, relief and safety valves. The module also includes the volume control tank with pump and valve. Fig. 3.1. shows the pressurizer module.

3.1. Pressure calculation

Four combinations of thermodynamic states of water and gas phases within the pressurizer are comprised by the model: gas in saturated or superheated state and water in saturated or subcooled state. Energy and mass balance are used to calculate the pressure and water level. It is assumed that no heat exchange takes place through the tank wall. Also enthalpies of surge tube and spray cooling water are assumed equal to hot and cold leg conditions respectively. The gas and water phases are described as homogeneous. Steam bubles and spray cooling droplets are considered to belong to the gas and water phase, i.e. the calculated water level may deviate slightly from a measured level.

In the derivations below the following notation is used: ρ density, V volume, p pressure, m mass, and h specific enthalpy. Indices: f water phase, g gas phase, s saturation.

First the water phase in saturation is described. Mass and energy balance gives

$$\frac{dm_{fs}}{dt} = \frac{d}{dt}(\rho_{fs}V_f) = W_i+W_c-W_e$$

$$\frac{d}{dt}(\rho_{fs}V_f h_{fs}) = Q+W_i h_i+W_c h_{fs}-W_e h_{gs}+V_f\dot{p} \qquad (3.1)$$

where W_i and h_i are mass flow to pressurizer and enthalpy from surge tube, W_c is the condensation rate in gas phase, W_e the evaporation rate in water phase and Q heating power in water phase. Eq. (3.1) transform into

$$\dot{V}_f = (W_i+W_c-W_e-V_f \frac{\partial \rho_{fs}}{\partial p_s} \dot{p})/\rho_{fs} \tag{3.2.a}$$

$$W_e = (Q-W_i^+(h_{fs}-h_i)-V_f(\rho_{fs} \frac{\partial h_{fs}}{\partial p_s} - 0.1)\dot{p})/h_{fg} \tag{3.2.b}$$

where W_i^+ is the positive part of W_i and $h_{fg} = h_{gs}-h_{fs}$ is the evaporation heat. The number 0.1 appears because non-SI units are used (cf. appendix A1).

Under subcooled conditions mass and energy balance give

$$\begin{aligned} \frac{dm_f}{dt} &= \frac{d}{dt}(\rho_f V_f) = W_i+W_c \\ \frac{d}{dt}(\rho_f V_f h_f) &= Q+W_i h_i+W_c h_{fs}+V_f\dot{p} \end{aligned} \tag{3.3}$$

which transforms into

$$\dot{V}_f = (W_i+W_c-V_f((\frac{\partial \rho_f}{\partial h})_p \dot{h}_f+(\frac{\partial \rho_f}{\partial p})_h \dot{p}))/\rho_f \tag{3.4.a}$$

$$\dot{h}_f = (Q+W_c(h_{fs}-h_f)-W_i^+(h_f-h_i)+0.1V_f\dot{p})/V_f\rho_f \tag{3.4.b}$$

Under saturated conditions the water enthalpy h_f (which is a state variable in the model) follows saturation value smothly as

$$\dot{h}_f = (h_{fs}-h_f)/0.25 \tag{3.2.c}$$

i.e. with a time delay of 0.25 sec. In the subcooled state

$$W_e = 0 \tag{3.4.c}$$

That is, water in saturated state is given from (3.2.a+b+c) and in subcooled state from (3.4.a+b+c).

Mass and energy balance for the gas phase in saturated state gives

$$\frac{dm_{gs}}{dt} = \frac{d}{dt}(\rho_{gs}V_g) = W_e+W_k-W_c-W_r$$
$$\frac{d}{dt}(V_g\rho_{gs}h_{gs}) = W_eh_{gs}+W_kh_k-W_ch_{fs}-W_rh_{gs}+V_g\dot{p} \tag{3.5}$$

where W_k and h_k are spray cooling rate and enthalpy of spray cooling water and W_r is the flow of steam leaving as leak in gas phase and through relief and safety valves.

Using $\dot{V}_g = -\dot{V}_f$ eq. (3.5) transform into

$$\dot{p} = (\rho_{gs}\dot{V}_f+W_e+W_k-W_c-W_r)/V_g\frac{\partial\rho_{gs}}{\partial p_s} \tag{3.6.a}$$

$$W_c = (W_k(h_{gs}-h_k)+V_g(\rho_{gs}\frac{\partial h_{gs}}{\partial p_s}-0.1)\dot{p})/h_{fg} \tag{3.6.b}$$

For the superheated state

$$\frac{dm_g}{dt} = W_e+W_k-W_r$$
$$\frac{d}{dt}(V_g\rho_gh_g) = W_eh_{gs}+W_kh_k-W_rh_{gs}+V_g\dot{p} \tag{3.7}$$

which turn into

$$\dot{p} = (W_e+W_k-W_r+\rho_g\dot{V}_f-V_g(\frac{\partial\rho_g}{\partial h})_p\dot{h}_g)/V_g(\frac{\partial\rho_g}{\partial p})_h \tag{3.8.a}$$

$$\dot{h}_g = (W_e(h_{gs}-h_g)-W_k(h_g-h_k)+0.1V_g\dot{p})/V_g\rho_g \tag{3.8.b}$$

Under saturated conditions gas enthalphy follows the saturation value

$$\dot{h}_g = (h_{gs}-h_g)/0.25 \tag{3.6.c}$$

and in the superheated state

$$W_c = 0 \tag{3.8.c}$$

That is, gas is described by (3.6.a+b+c) in saturated state and (3.8.a+b+c) in superheated state.

In the water phase the switch from saturation to subcooling takes place when W_e reaches zero and switching from subcooled to saturated state happens when h_f reaches h_{fs} from the lower side. Similar switches takes place in gas phase: from saturation to superheated state when W_c reaches zero and from superheated to saturated state, when h_g reaches h_{gs} from the higher side. The state of the system determines which two of the four sets of equations (3.2), (3.4), (3.6), and (3.8) are to be used. However, the state itself is determined by values of variables calculated by these equations. This implicitness is solved by two iterations in which the equations are applied and the state is determined.

Another implicitness arises using the equations for V_f and p. Therefore these equations are combined and solved for p. As an example consider the case of saturation in both phases. Rewriting (3.6.a) and using (3.2.a) yields

$$V_g \frac{\partial \rho_{gs}}{\partial ps} \dot{p} = \rho_{gs}\dot{V}_f+W_e+W_k-W_c-W_r$$

$$= \frac{\rho_{gs}}{\rho_{fs}} (W_i+W_c-W_e-V_f\frac{\partial \rho_{fs}}{\partial p_s}\dot{p})+W_e+W_k-W_c-W_r$$

which gives

$$(V_g\frac{\partial \rho_{gs}}{\partial ps} + \frac{\rho_{gs}}{\rho_{fs}} V_f\frac{\partial \rho_{fs}}{\partial p_s})\dot{p} = (1-\frac{\rho_{gs}}{\rho_{fs}})W_e + (\frac{\rho_{gs}}{\rho_{fs}}-1)W_c+\frac{\rho_{gs}}{\rho_{fs}}W_i-W_r+W_k$$

or

$$F_c\dot{p} = (1-\frac{\rho_{gs}}{\rho_{fs}})W_e + (\frac{\rho_{gs}}{\rho_{fs}}-1)W_c+ \frac{\rho_{gs}}{\rho_{fs}} W_i-W_r+W_k$$

where

$$F_c = V_g \frac{\partial \rho_{gs}}{\partial p_s} + \frac{\rho_{gs}}{\rho_{fs}} V_f \frac{\partial \rho_{fs}}{\partial p_s}$$

A similar "compressibility factor" F_c to $\dot{p}$ appears in the three other combinations of states (i.e. with and without index s to the gas and water term). The pressure derivative of ρ is evaluated for constant enthalphy.

Calculating pressure p as a global variable for the whole primary circuit it is necessary to extend the water term of F_c with similar terms for all individual volumes in the primary system as

$$F_c = V_g \frac{\partial \rho_g}{\partial p} + V_f \frac{\rho_g}{\rho_f} \frac{\partial \rho_f}{\partial p} + \rho_g \sum_j V_{f,j} \frac{\partial \rho_{f,j}}{\partial p} \frac{1}{\rho_{f,j}} \tag{3.9}$$

where derivatives of ρ for the external volumes are taken for constant temperature.

The inlet flow W_i through the surge tube is calculated as

$$W_i = \rho_{fi} \sum_j V_{f,j} \left(\frac{\partial \rho_{f,j}}{\partial T}\right)_h \frac{1}{\rho_{f,j}} \dot{T}_{f,j}$$

$$- \dot{p}\, \rho_{fi} \sum_j V_{f,j} \left(\frac{\partial \rho_{f,j}}{\partial p}\right)_T \frac{1}{\rho_{f,j}} \tag{3.10}$$

$$+ \frac{\rho_{fi}}{\rho_{fl}} (W_{cha} - W_{led} - W_k - Leak_f)$$

where ρ_{fi} and ρ_{fl} are densities of hot and cold leg water, and $Leak_f$ is the total water phase leak. The first term gives the thermal expansion rate from all external volumes, the second term accounts for the mass absorption in the primary system due to pressure variations as stated above and the last term corrects for flows from and to the volume control tank and for spray cooling rate. The individual terms in the summation over external volumes are calculated in the reactor and steam generator module and given as input to the pressurizer module.

The relative mass of water in the volume control tank m_{VCTR} is calculated from mass balance as

$$\frac{dm_{VCTR}}{dt} = (W_{led}-W_{cha})/m_{VCTP}$$

where m_{VCTP} is the total mass capacity of the tank. No energy treatment is given to the volume control tank.

3.2. Controller actions

The pressure controller output signal (cf. section 9) controls relief valve 1, spray valve and heater system. Relief valve 2 and the safety valve acts directly on the pressure signal. The respond characteristics of these components to pressure controller output signal and pressure signal are shown in Fig. 3.2. The safety valve opens at pressure above 172.4 bar with a capacity of 49.7 kg/s. An overwriting action on heaters from water level is not shown on Fig. 3.2. Below 15% level all heaters are disconnected and when the level is more than 5% above the level controller setpoint the backup heaters are turned on. Both actions are independent of the controller signal.

The level is measured with a span of 10.29 m. Normal level is defined as 47.8% with V_f = 19.82 m^3. With the tank cross section, A, equal to 3.67 m^2, 0 and 100% water level corresponds to the volumes 1.77 and 39.53 m^3, respectively. The cross section is assumed to be constant over the level span so the relative level W_{lv} can be expressed as:

$$W_{lw} = (V_f-1.77)/37.76$$

The volume control tank pump gives a flow proportional to the level controller output signal. The flow into the volume control tank W_{led} is constant at a value specified as input by the user.

3.3. Failures

Various failures can be simulated in the pressurizer module. The proportional and backup heaters can be turned off by switches, i.e. the heating power is zero independent of controller signal. Failures in relief valves and spray valve cause these valves to remain fixed at the valve position when the failure signal is set. A failure signal to the safety valve causes the valve to open normally but to leak 0.5% of the fully-open flow on return to closed state. Further a pump flow fraction on the volume control tank pump can be specified. Leaks from the primary circuit are handled in the pressurizer module (except for the primary to secondary side). Leaks from gas and water phase can be simulated. For further details of failures and disturbances are referred to section 10.

Physical data and steady state values used in the pressurizer module are found in appendix A3.

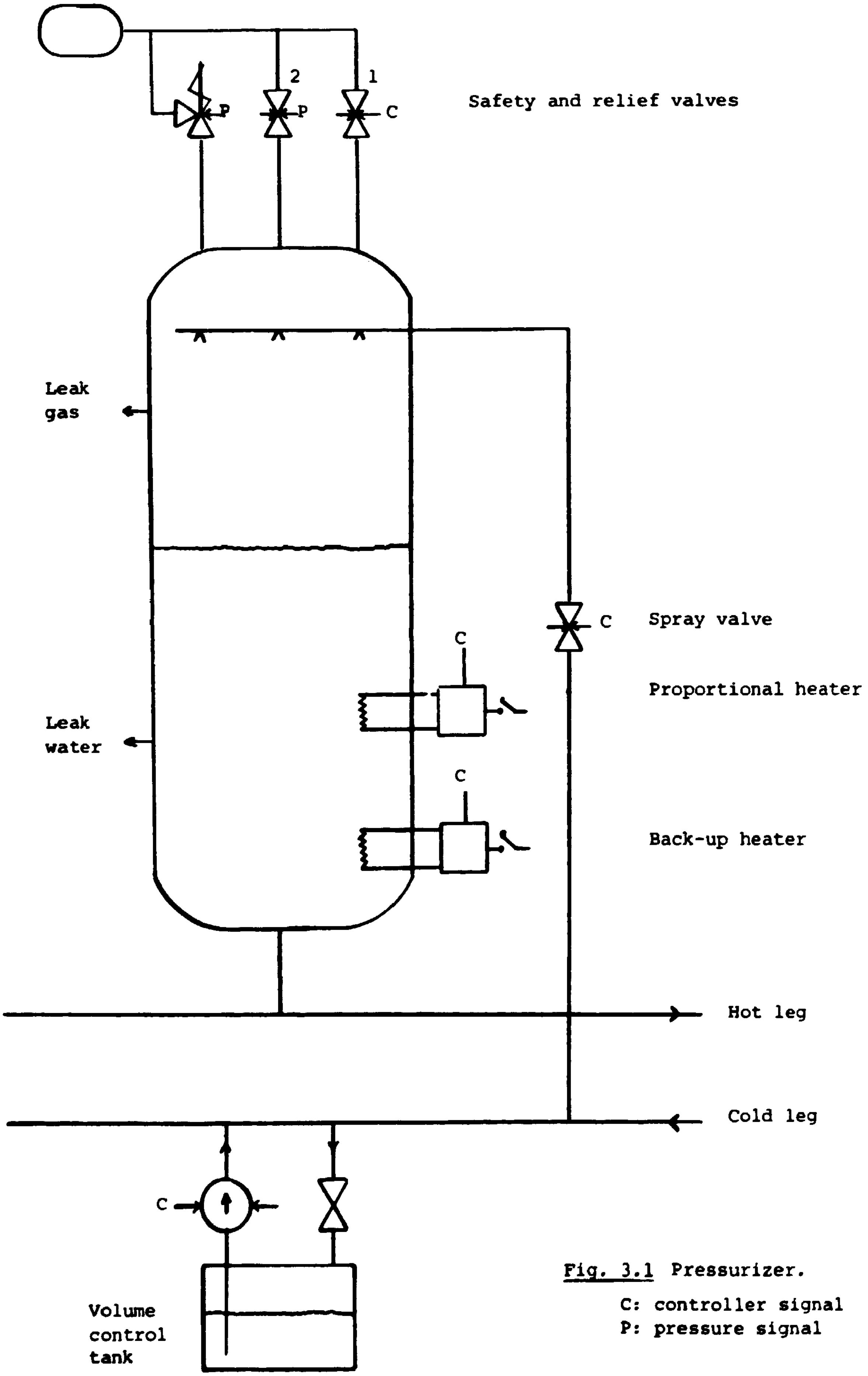


Fig. 3.1 Pressurizer.

C: controller signal
P: pressure signal

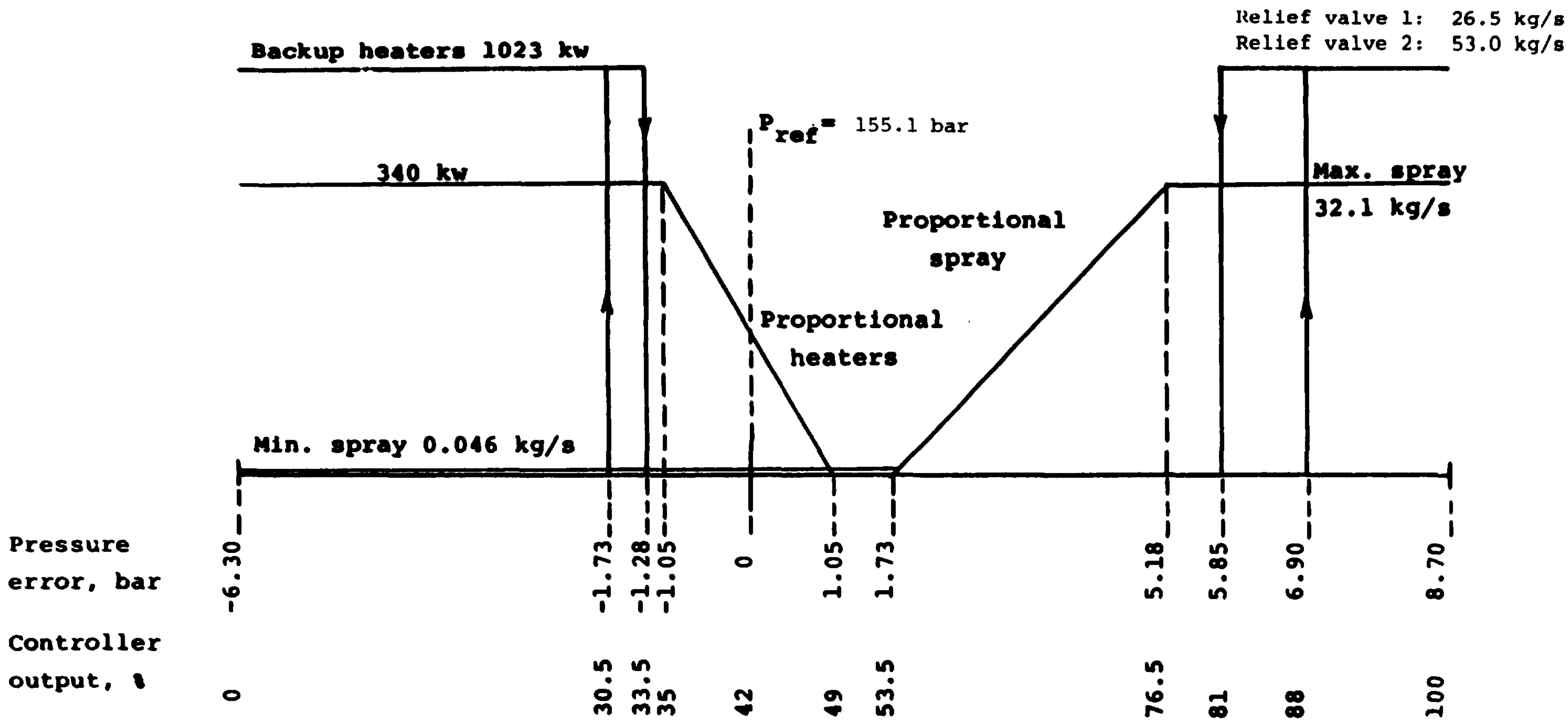


Fig. 3.2 Pressure control.

4. CONTAINMENT ACTIVITY

Radioactivity release from the primary circuit in case of leaks are handled in a very crude model. The activity is assumed to be confined to the containment. This means that a possible leak from primary to secondary side is not considered in terms of activity.

Leaks of water and steam from the primary side can be simulated. The steam leak takes place from the pressurizer whereas water leak can be imagined to take place anywhere in the primary circuit.

Only activity due to ^{16}N in the primary water is modelled. ^{16}N is β-active with a half life of 7.13 s. An activity of 132 Q_{nuclr} Ci/m^3 in the hot leg and water phase of the pressurizer is assumed, where Q_{nuclr} is relative nuclear power.

This is transformed into a specific activity of the water phase as

$$A_{Rf} = \frac{132\ Q_{nuclr}\ \mathrm{Ci/m^3} \cdot 3.7 \cdot 10^{10}\ \mathrm{Bq/Ci}}{\rho_{fs}}$$

$$= 8.10 \cdot 10^9\ Q_{nuclr}\ \mathrm{Bq/kg}$$

The gas phase activity is taken as

$$A_{Rg} = 80\%\ A_{Rf} = 6.48 \cdot 10^9\ Q_{nuclr}\ \mathrm{Bq/kg}$$

The activity in the containment is then calculated as

$$\frac{dA_{CN16}}{dt} = (A_{Rg}L_g + A_{Rf}L_f)Q_{nuclr} - \lambda A_{CN16} \qquad (4.1)$$

where L_g and L_f are leaks (Kg/s) and the decay constant

$$\lambda = \frac{\ln 2}{7.13}\ \mathrm{s^{-1}}.$$

5. STEAM GENERATOR

The steam generator module is confined to the interior of the tank as shown in Fig. 5.1. Part of the primary circuit lies within the module: the primary inlet chamber, the U-tube which is divided into two sections and the primary outlet chamber. The secondary side of the steam generator is divided into the core section which surrounds the U-tube and where steam production takes place, above this the top chamber and riser sections, the mixing chamber where feedwater enters and the down comer. Steam is extracted from the steam chamber at the top.

The following notations will be used in the subsequent derivations: ρ is density, V volume, p pressure, m mass, c specific heat capacity, and h specific enthalpy. Indices: f water phase, g gas phase, and s saturation.

Temperature of water in the primary inlet chamber, T_i, is given from energy conservation

$$\rho_f V_{pi} \dot{T}_i = W_p(T_{pi}-T_i) \tag{5.1}$$

where T_{pi} is the hot leg water temperature, V_{pi} is the inlet chamber volume and W_p is the primary flow.

For both sections of the U-tube a mean primary temperature T_m is calculated from inlet and outlet temperature of the section T_i and T_o by a standard procedure (Appendix D). Now the heat transfer from primary side to the tubes is calculated as

$$Q_p = K_p(T_m-T_r) \tag{5.2}$$

where T_r is the tube temperature. The transfer coefficient K_p is calculated from the coefficient h_p for water to tube transfer and the coefficient h_r for transfer through the tube wall as

$$K_p = h_p h_r/(h_p+h_r)$$

where the Dittus-Boelter equation gives

$$h_p = \frac{0.023 \cdot 10^{-3}\ O_p L_c}{De_p^{0.2}\ A_p^{0.8}}\ W_p^{0.8}\ H_p(T_m) \tag{5.3}$$

Here O_p, L_c, De, and A_p are inner surface (m^2/m), length (of one U-tube section), hydraulic diameter and cross section of the U-tube. For details of the parameter H_p is referred to (Christensen 1981). The heat transfer coefficient, h_r, for the tube wall is constant

$$h_r = \frac{O_u L_c\ \lambda_r}{1/2\ dr} \tag{5.4}$$

where O_u, λ_r, and dr are surface (between inside and outside), thermal conductivity (MW/m·C) and tube thickness.

The heat transfer from U-tube to secondary side is calculated from

$$Q_s = K_s(T_r - T_{sat}) \tag{5.5}$$

where T_{sat} is the secondary side saturation temperature. The heat transfer coefficient K_s is again calculated from the coefficient h_s for tube to secondary side transfer and h_r as

$$K_s = h_s h_r/(h_s+h_r) \tag{5.6}$$

where the Thom correlation gives

$$h_s = 1.972 \cdot 10^{-3}\ O_s L_c\ \exp(p/43.4)(T_{ry} - T_{sat}) \tag{5.7}$$

Here O_s and p are outer surface and secondary side pressure. A tube surface temperature , T_{ry}, has been used,calculated from energy balance as

$$T_{ry} = \frac{Q_s}{h_s} + T_{sat} \tag{5.8}$$

in order to stabilize the calculations.

The tube wall temperature and primary outlet temperature is given from

$$C_r\dot{T}_r = Q_p - Q_s \tag{5.9}$$

$$\rho_f V_p c_p \dot{T}_o = -Q_p + c_p W_p(T_i - T_o) \tag{5.10}$$

where V_p and c_p are volumes and specific heat capacity of primary water in the U-tube. Equations (5.1) - (5.10) are given for both sections of the U-tube.

The primary outlet chamber temperature is now calculated from

$$\rho_f V_{po}\dot{T}_{po} = W_p(T_o - T_{po}) \tag{5.11}$$

where V_{po} is the volume of the outlet chamber.

The total heat transfer, Q_s, (from both U-tube sections) now gives the heat, Q_K, for steam production

$$Q_k = Q_s - W_s c_s(T_{sat} - T_d) \tag{5.12}$$

i.e. corrected for the heating of downcomer flow, W_s, from temperature T_d to saturation.

In the secondary core section mass and energy balance gives

$$\frac{dm}{dt} = \frac{d}{dt}(\rho_{fs}V_{fs}) + \frac{d}{dt}(\rho_{gs}V_{gs}) = W_s + L_p - W_{fs} - W_{gs}$$

$$\frac{d}{dt}(\rho_{fs}V_{fs}h_{fs}) + \frac{d}{dt}(\rho_{gs}V_{gs}h_{gs}) = \tag{5.13}$$

$$Q_k + L_p h_p + W_s h_{fs} - W_{fs}h_{fs} - W_{gs}h_{gs} - V_s\dot{p}$$

where V_{fs} and V_{gs} are water and void volumes, W_{fs} and W_{gs} are water and steam flows out of the core region, L_p and h_p are leak from primary to secondary side and enthalpy of primary water, and V_s is the core volume. Eq. (5.13) transforms into

$$W_{fs} = W_s+L_p-W_{gs}+\dot{V}_{gs}(\rho_{fs}-\rho_{gs})-\dot{p}(\frac{\partial\rho_{fs}}{\partial p_s} V_{fs} + \frac{\partial\rho_{gs}}{\partial p_s}V_{gs}) \qquad (5.14)$$

$$\dot{V}_{gs} = \frac{1}{\rho_{gs}}(\frac{Q_k+L_p(h_p-h_{fs})}{h_{fg}} - \frac{\dot{p}}{h_{fg}}(V_{gs}(\rho_{gs}\frac{\partial h_{gs}}{\partial p_s} + h_{fg}\frac{\partial\rho_{gs}}{\partial p_s})$$

$$+ V_f\rho_{fs}\frac{dh_{fs}}{dp_s} - 0.1V_s)-W_{gs}) \qquad (5.15)$$

where the number 0.1 appears because of use of non-SI units (cf. Appendix A1).

Now the steam flow out of the core region is calculated as

$$W_{gs} = S(\alpha_s)\, W_{fs}\, \frac{\alpha_s}{1-\alpha_s}\, \frac{\rho_{gs}}{\rho_{fs}} \qquad (5.16)$$

where

$$\alpha_s = F_\alpha(\frac{V_{gs}}{V_s})\, \frac{V_{gs}}{V_s} \qquad (5.17)$$

A steam to water slip correlation $S(\alpha_s)$ given by Bankoff-Jones is used (c.f. Nash 1980). An empirical relation F_α between relative void volume V_{gs}/V_s and outlet void fraction α_s is used (cf. Christensen, 1974, Fig. 12).

The equations (5.14) - (5.17) form an algebraic loop which is solved by inserting the expressions (5.16) and (5.15) for W_{gs} and $\dot{V}_{gs}$ into (5.14) and solving this equation for W_{fs}. The derived expression for W_{fs} is then inserted into (5.16) and (5.15).

In the top chamber and riser sections the equations for void volume and water outlet flow are derived in similar way. Only equations for the riser section are presented. The equations for the top chamber are the same except for an exchange of riser index r with top chamber index t.

Energy and mass balance gives

$$\frac{dm}{dt} = \frac{d}{dt}(\rho_{fs}V_{fr}) + \frac{d}{dt}(\rho_{gs}V_{gr}) = W_{ft}+W_{gt}-W_{fr}-W_{gr}$$

$$\frac{d}{dt}(\rho_{fs}V_{fr}h_{fs}) + \frac{d}{dt}(\rho_{gs}V_{gr}h_{gs}) \tag{5.18}$$

$$= W_{ft}h_{fs}+W_{gt}h_{gs}-W_{fr}h_{fs}-W_{gr}h_{gs}+V_r\dot{P}$$

Where W_{ft}, W_{gt}, W_{fr}, and W_{gr} are water and steam outlet flows from top chamber and riser. Eq. (5.18) transforms into

$$W_{fr} = W_{ft}+W_{gt}-W_{gr}+\dot{V}_{gr}(\rho_{fs}-\rho_{gs})-\dot{p}(\frac{\partial\rho_{fs}}{\partial p_s}V_{fr}+\frac{\partial\rho_{gs}}{\partial p_s}V_{gr}) \tag{5.19}$$

$$\dot{V}_{gr} = \frac{1}{\rho_{gs}}((W_{gt}-W_{gr}) - \frac{\dot{p}}{h_{fg}}(V_{gr}(\rho_{gs}\frac{\partial h_{gs}}{\partial p_s} + h_{fg}\frac{\partial\rho_{gs}}{\partial p_s})$$

$$+ V_{fr}\rho_{fs}\frac{\partial h_{fs}}{\partial p_s} - 0.1\ V_r) \tag{5.20}$$

As for the core section

$$W_{gr} = S(\alpha_r)\ W_{fr}\frac{\alpha_r}{1-\alpha_r}\frac{\rho_{gs}}{\rho_{fs}} \tag{5.21}$$

$$\alpha_r = F_\alpha(\frac{V_{gr}}{V_r})\frac{V_{gr}}{V_r} \tag{5.22}$$

Now the pressure is calculated from mass balance in the steam chamber

$$\frac{dm}{dt} = \frac{d}{dt}(\rho_{gs}V_{top}) = \rho_{gs}\dot{V}_{top} + \dot{\rho}_{gs}V_{top} \tag{5.23}$$

$$\sim \rho_{gs}\dot{V}_{top} + \frac{\partial\rho_{gs}}{\partial p_s}\dot{p}V_{top} = W_{gr}-W_L-L_g$$

using $\dot{V}_{top} = - A_b \dot{l}$ this gives

$$\dot{p} = \frac{W_{gr}-W_l-L_g+\rho_{gs}A_b\dot{l}}{V_{top}\,\dfrac{\partial\rho_{gs}}{\partial p_s}} \tag{5.24}$$

Here W_l and L_g are the steam load and a possible leak of steam; l ans A_b are water level and cross section of the mixing chamber.

In order to improve numerical stability $\dot{p}$ is actually calculated before it is used in equations (5.14) - (5.20). Further a delayed pressure derivative, dp, is calculated as

$$\dot{dp} = (\dot{p}-dp)/\tau_p \tag{5.25}$$

and used instead of $\dot{p}$ in the former equations. This will cause fast oscillations in pressure to be damped when used to calculate the void volumes.

The temperatures in the mixing chamber and downcomer, T_b and T_d, are now calculated from energy balance

$$\rho_{fs}V_b\dot{T}_b = W_{fr}T_{sat} + W_iT_i\,\frac{c_{pi}}{c_{ps}} - (W_{fr}+W_i)T_b - \rho_{fs}A_bT_b\dot{l} \tag{5.26}$$

$$\rho_{fs}V_{dc}\dot{T}_d = W_s(T_b-T_d) \tag{5.27}$$

Here W_i, T_i, and c_{pi} are feedwater inlet flow, temperature, and specific heat capacity, V_b and V_{dc} volumes of mixing chamber and downcomer and W_s the downcomer flow.

The flow rate in the downcomer, v_d, is calculated from the momentum equation of the closed hydraulic loop

$$\frac{dJ}{dt} = D - \Delta p_f \tag{5.28}$$

where J is the total momentum per unit area in the loop, D is the driving pressure from gravity due to density differences in the loop, and Δp_f is the pressure drops from friction forces. Using the flow direction as positive direction, $g = +9.82\ m/s^2$ as the gravitational acceleration and assuming that all momentum lies in the water phase, eq. (5.28) is written as

$$\rho_{fs}\frac{V_{fs}}{A_s}\dot{v}_s + \rho_{fs}\frac{V_{ft}}{A_t}\dot{v}_t + \rho_{fs}\frac{V_{fr}}{A_r}\dot{v}_r + \rho_{fs}\frac{V_{dc}}{A_d}\dot{v}_d =$$

$$(-\rho_{gs}\frac{V_{gs}}{A_s}-\rho_{fs}\frac{V_{fs}}{A_s}-\rho_{gs}\frac{V_{gt}}{A_t}-\rho_{fs}\frac{V_{ft}}{A_t}-\rho_{gs}\frac{V_{gr}}{A_r}-\rho_{fs}\frac{V_{fr}}{A_r}+\rho_{fs}l+\rho_{fs}\frac{V_{dc}}{A_d})g$$

$$-\Delta p_s-\Delta p_t-\Delta p_r-\Delta p_d \qquad (5.29)$$

Here A, v, and Δp are cross sections, flow rate, and friction pressure drops in core (s), top chamber (t), viser (r), and downcomer (d). V_{dc} is the downcomer volume. Assuming now that

$$v_yA_y = v_d\ A_d; \qquad y = s,t,r$$

(5.29) is transformed into an equation for $\dot{v}_d$

$$((1-\alpha_s)\frac{l_c}{A_s} + (1-\alpha_t)\frac{l_t}{A_t} + (1-\alpha_r)\frac{l_r}{A_r} + \frac{l_d}{A_d})A_d\ \dot{v}_d =$$

$$((-l_c(\frac{\rho_{gs}}{\rho_{fs}}\alpha_s+1-\alpha_s)-l_t(\frac{\rho_{gs}}{\rho_{fs}}\alpha_t+1-\alpha_t)-l_r(\frac{\rho_{gs}}{\rho_{fs}}\alpha_r+1-\alpha_r)+l+l_d)g$$

$$-\frac{1}{\rho_{fs}}(\Delta p_s+\Delta p_t+\Delta p_r+\Delta p_d) \qquad (5.30)$$

where l_c, l_t, l_r, and l_d are lengths of core, top chamber, riser and down comer sections.

The friction pressure drops are calculated from (cf. Christensen 1974, p. 30) as

$$\frac{\Delta p_s}{\rho_{fs}} = \frac{0.092\ K_{dps}}{De_s^{1.2}}\ F_f\ l_c(\frac{W_{gs}+W_{fs}}{\rho_{fs}A_s})^2(1+2400\frac{W_{gs}}{(W_{fs}+W_{gs})p}) \qquad (5.31)$$

and similar expression for the top chamber and riser with index s exchanged with t and r. For the downcomer section

$$\frac{\Delta p_d}{\rho_{fs}} = \frac{0.092}{De_d^{1.2}} \; F_f \; K_{dpd} \; L_d \; v_d^2 \qquad (5.32)$$

is used.

The factor $F_f = (\eta/\rho)^{0.2}$ is the single phase friction factor for smooth tubes with the hydraulic diameter De, and K_{dp} is an arbitrary correction factor for the geometry chosen to give a realistic recirculation rate. The last term in eq. (5.31) is the socalled two phase flow friction multiplier dependent of pressure and steam quality $W_g/(W_g+W_f)$.

Finally mass balance for the mixing chamber gives the water level l

$$A_b \; \rho_{fs} \; \dot{l} = W_{fr}+W_i-W_s \qquad (5.33)$$

All physical constants used in the module and steady state values are found in appendix A5.

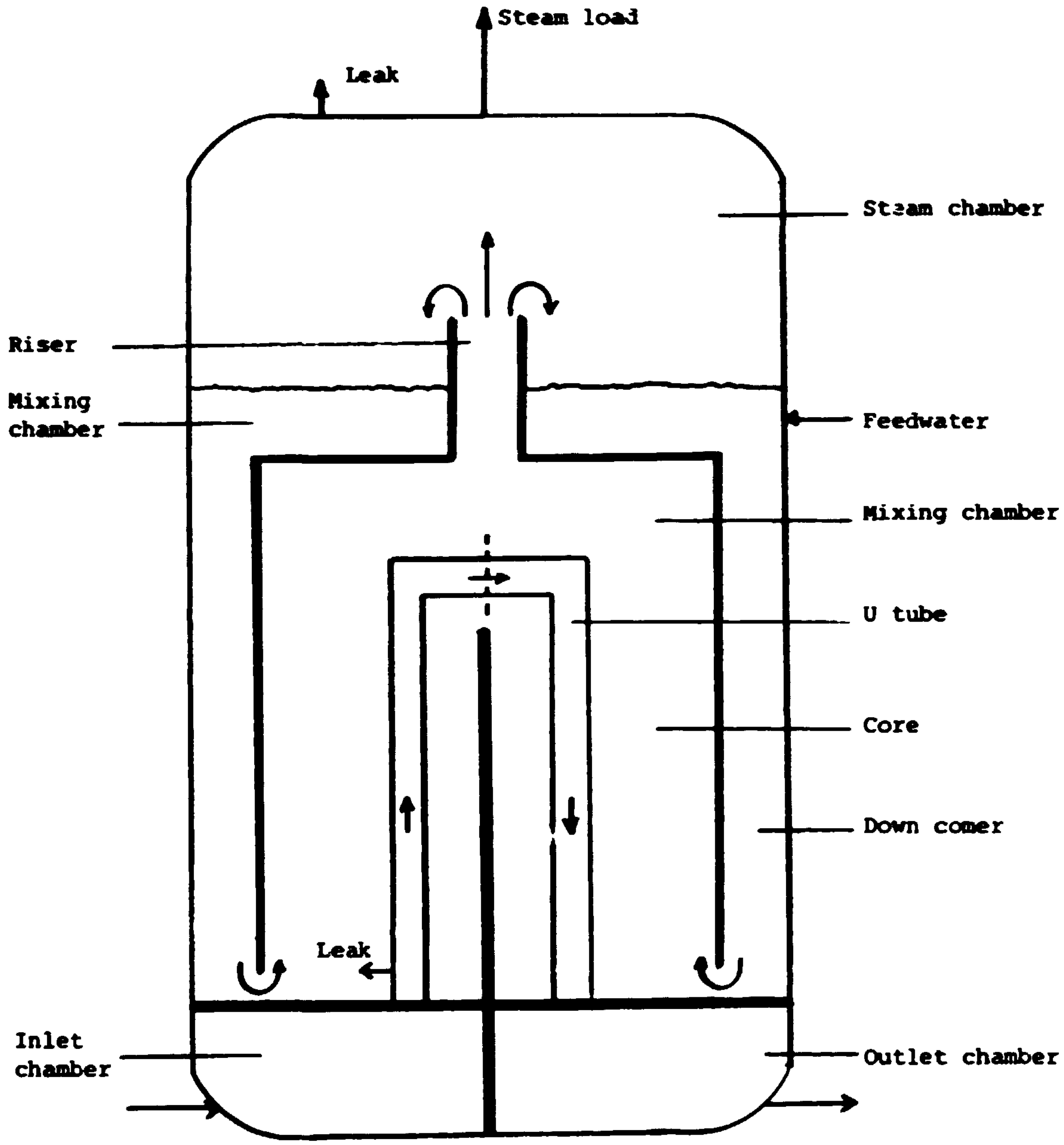


Fig. 5.1 Steam generator.

6. TURBINES AND CONDENSER

This module comprises the steam line, high pressure (HP) and low pressure(LP) turbines, moisture separator, reheater, and condenser as shown in Fig. 6.1. Steam from the steam generator enters the steam line. One steam flow is led through the HP-turbine. In the outlet flow from this turbine water is separated and the steam is superheated in the reheater by a flow from the steam line. The superheated steam enters the LP-turbine and the outlet flow from this turbine is led to the condenser. Steam is extracted from the HP-and LP-turbines for preheating the feed-water. The outlet flows from the moisture separator and the reheater are led to the feedwater tank (cf. section 7). In the derivations below the following notation is used: ρ density, h and c specific enthalpy and heat capacity, index f, g, and s for gas, water, and saturation.

6.1. Steam line

The steam line flow (steam load) W_{sl} is calculated from

$$W_{sl} = \sqrt{\frac{p_e - p_v}{k_e}} \tag{6.1}$$

where p_e is the steam generator pressure and p_v the steam line outlet pressure. The steam line outlet pressure is calculated from mass balance (cf. eq. (5.23))

$$\dot{p}_v = \frac{W_{sl} - (W_v + W_b + W_m + W_{rv} + W_{sv})}{V_{sl}\,\dfrac{\partial \rho_{gs}}{\partial p_s}} \tag{6.2}$$

where W_v, W_b, W_m, W_{rv}, and W_{sv} are HP-turbine valve flow, by-pass flow, reheater flow, relief- and safety valve flows.

The HP-turbine valve flow is given as input to the module and calculated as part of the turbine controller system (cf. section 9). The by-pass flow is given by

$$W_b = K_b x_{bpv} p_v \tag{6.3}$$

where x_{bpv} is the by-pass valve control signal (valve position). The reheater flow is calculated from

$$W_m = K_{vm} A_{mov} x_{rhv} (p_v - p_m) \tag{6.4}$$

where p_m is the primary side reheater pressure and x_{rhv} is a user specified valve position (normally $x_{rhv} = 1$). The relief valve flow is given by

$$W_{rv} = K_{rv} x_{rv} p_v \tag{6.5}$$

where x_{rv} is the relief valve controller signal (valve position). In all six safety valves are present but lumped together in cn valve in the model. The first valve opens at 82 bar, then the others follow at 83, 84, 85, 86, and 87 bar. Each valve opens lineary with increasing steam line pressure within a pressure interval of 3% of the opening pressure. The total safety valve flow is then calculated as

$$W_{sv} = K_{sv} \sum_{i=1}^{6} x_i \tag{6.6}$$

where x_i is the i'th valve position.

6.2. HP-turbine

The HP-turbine inlet flow (W_h) is calculated from (cf. Christensen et al. 1984, p. 15)

$$W_h = \begin{cases} K_h p_h & \text{for } p_t/p_h < 0.7 \\ K_h p_h \left(1 - \frac{100}{9}\left(\frac{p_t}{p_h} - 0.7\right)^2\right) & \text{for } p_t/p_h \geq 0.7 \end{cases} \tag{6.7}$$

where p_h and p_t are pressures of HP-turbine inlet chamber and secondary side reheater. Normally the flow is proportional to the inlet pressure (upper case) but at abnormal low pressure conditions when the outlet to inlet pressure ratio approaches one the flow vanishes. This situation is taken care of by the lower case formula.

Mass balance in the HP-inlet chamber gives the pressure

$$\dot{P}_h = \frac{W_v - W_h}{V_h \frac{\partial \rho_{gs}}{\partial p}} \tag{6.8}$$

where V_h is the HP-inlet chamber volume.

The total enthalpy in the HP-inlet chamber is calculated from

$$\dot{H}_{hp} = W_v h_v - W_h h_h \tag{6.9}$$

where the steam line specific enthalpy (h_v) is assumed to contain 0.5% humidity, i.e.

$$h_v = 0.995\ h_{gs}(P_e) + 0.005 h_{fs}(P_e) \tag{6.10}$$

The specific enthalpy of the inlet chamber is then given from

$$h_h = \frac{H_{hp}}{V_h\ \rho'_{gh}\ P_h} \tag{6.11}$$

where V_h is the inlet chamber volume and

$$\rho'_{gh} = \frac{\partial \rho_{gs}}{\partial p_s}$$

The steam expansion and variation of steam conditions in the turbines are described by the Mollier diagram in equational form using thermal efficiencies determined from the static data. The calculational procedure is as follows: (cf. Christensen et al. 1984)

First, the inlet steam quality X and entropy S are found from enthalphy h and pressure p. Then, the outlet quality and enthalpy are found for isentropic expansion with known outlet pressure.

Afterwards, the real enthalpy drop Δh is found with a known thermal efficiency γ, and finally the real outlet values for the enthalpy and steam quality can be calculated.
The equations for the HP-turbine are:

$$
\begin{aligned}
X_h &= (h_h-h_{fs}(p_h))/(h_{gs}(p_h)-h_{fs}(p_h)) \\
S_h &= X_h S_{gs}(p_h) + (1-X_h)S_{fs}(p_h) \\
X_{ho} &= (S_h-S_{fs}(p_t))/(S_{gs}(p_t)-S_{fs}(p_t)) \\
h_{ho} &= X_{ho}h_{gs}(p_t) + (1-X_{ho})h_{fs}(p_t) \\
\Delta h_h &= (h_n-h_{ho})\gamma_h \\
h_{ho} &= h_h-\Delta h_h \\
X_{ho} &= (h_{ho}-h_{fs}(p_t))/(h_{gs}(p_t)-h_{fs}(p_t))
\end{aligned}
\tag{6.12}
$$

where S_{gs} and S_{fs} are functions for the saturation entropy of steam and water.

The outlined procedure is described in a standard routine which also handles the superheated inlet steam case in the LP-turbine.

Steam is extracted from the HP-turbine for the feedwater preheater. The flow W_{phh} is given as input and calculated in the feedwater line module (cf. section 7). The extraction pressure (P_{sh}) and enthalpy (h_{sh}) are calculated from

$$
\begin{aligned}
p_{sh} &= p_h-S_{plith}(p_h-p_t) \\
h_{sh} &= h_h-S_{plith}(h_h-h_{ho})
\end{aligned}
\tag{6.13}
$$

where S_{plith} is the fraction of the total pressure and enthalpy drop through the turbine.

The turbine power is now calculated as

$$E_h = W_h(h_h-h_{ho}) - W_{phh}(h_{sh}-h_{ho}) \tag{6.14}$$

6.3. Reheater

The reheater is divided into two sections, the moisture separator and the superheater. The inlet flow from the HP-turbine is given from

$$W_t = W_h - W_{phh} \tag{6.15}$$

After the water has been separated from the flow in the moisture separator the steam is assumed to contain 0.5% humidity, i.e. the inlet flow without water is

$$W_{ti} = \frac{x_{ho}}{0.995} W_t \tag{6.16}$$

and the specific inlet enthalpy is

$$h_{ti} = 0.995\ h_{gs}(p_t) + 0.005\ h_{fs}(p_t) \tag{6.17}$$

Only one pressure node is used for the whole reheater, i.e. pressure is determined by

$$\dot{p}_t = \frac{W_{ti} - W_{ro}}{(V_t + V_r)\ \dfrac{\partial \rho_{gs}}{\partial p}} \tag{6.18}$$

where V_t and V_r are volumes of the moisture separator and superheater compartments and W_{ro} is the reheater outlet flow. This flow is calculated from

$$W_{ro} = K_{hl}\ A_{ltv} x_{lpv} (p_t - p_l) \tag{6.19}$$

where p_l is the LP-turbine inlet chamber pressure and x_{lpv} is a user specified valve position (normally $x_{lpv} = 1$).

The steam flow, W_{to}, from the moisture separator to the superheater section is calculated as a mean value of the reheater inlet and outlet flows

$$W_{to} = \frac{V_r W_{ti} + V_t W_{ro}}{V_t + V_r} \tag{6.20}$$

Energy balance then gives the total enthalpy in the moisture separator compartement as

$$\dot{H}_{rtv} = W_{ti} h_{ti} - W_{to} h_{to} \tag{6.21}$$

where the specific enthalpy is

$$h_{to} = \frac{H_{rtv}}{V_t \dfrac{\partial \rho_{gs}}{\partial p} \; p_t} \tag{6.22}$$

Energy balance for the secondary side of the superheater gives the total and specific enthalpy

$$\dot{H}_{rhv} = W_{to} h_{to} + Q_{rr} - W_{ro} h_{ro} \tag{6.23}$$

$$h_{ro} = \frac{H_{rhv}}{V_t \dfrac{d\rho_{gs}}{dp} \; p_t} \tag{6.24}$$

where Q_{rr} is the heat transfer from tube to steam, calculated as

$$Q_{rr} = K_{qr}(T_{tr} - T_{rm}) \tag{6.25}$$

Here T_{tr} is the tube temperature and T_{rm} is a superheater mean temperature calculated from inlet ($T_{r.o}$) and outlet temperature (T_{ro}) (cf. appendix D). The outlet temperature, T_{ro}, is given from

$$T_{ro} = T_{sat}(p_t) + \frac{h_{ro} - h_{gs}(p_t)}{c_{pr}} \tag{6.26}$$

The heat transfer constant of eq. (6.25) is calculated from

$$K_{qr} = \frac{W_{ro}}{C_{Kqr}} \tag{6.27}$$

The heat transfer Q_{tr} from the reheater primary side to the tube is given by

$$Q_{tr} = K_{qt}(T_m - T_{tr}) \tag{6.28}$$

where T_m is the saturation temperature of steam, given from the primary side pressure p_m .

Energy balance then gives the tube temperature

$$\dot{T}_{tr} = \frac{Q_{tr} - Q_{rr}}{C_{tr}} \tag{6.29}$$

where C_{tr} is the tube heat capacity. The flow leaving the reheater primary side is now calculated as

$$W_{mc} = \frac{Q_{tr}}{h_v - h_{fs}(p_m)} \tag{6.30}$$

and the primary side pressure is calculated from mass balance as

$$\dot{p}_m = \frac{W_m - W_{mc}}{V_{mo} \dfrac{\partial \rho_{gs}}{\partial p_s}} \tag{6.31}$$

6.4. LP-turbine

The equations for the LP-turbine section are the same as for the HP-turbine with indices h and h_p exchanged with 1 and 1_p. The flow to the LP-turbine inlet chamber is the previous calculated W_{ro} and the turbine outlet pressure is the condenser pressure, p_c.

The total turbine power is the sum of HP- and LP-turbine power

$$E = E_h + E_1 \tag{6.32}$$

6.5. Condenser

The LP-turbine outlet flow, W_{lo}, and a possible by-pass flow, W_b, are condensed on the tubes in the condenser. It is assumed that the condenser is in saturated state, i.e. the condensate and tube temperature, T_{con}, is the saturation temperature. From this temperature the condenser pressure is given as

$$p_c = p_{sat}(T_{con}) \tag{6.33}$$

The heat transferred to the tube is given by

$$Q_{ct} = W_{lo}(h_c - h_{fs}(p_c)) + W_b(h_v - h_{fs}(p_c)) \tag{6.34}$$

where h_c is the LP-turbine outlet enthalpy.

A mean cooling water temperature, T_{cm}, in the tube is calculated from the inlet (T_{ci}) and outlet temperature, T_{co}, (cf. appendix D). Then the heat transfer from tube to coolant is given from

$$Q_{cv} = K_{cw}(T_{con} - T_{cm}) \tag{6.35}$$

Energy conservation gives the tube and coolant outlet temperature as

$$\dot{T}_{con} = \frac{Q_{ct} - Q_{cv}}{C_{ct}} \tag{6.36}$$

$$\dot{T}_{co} = \frac{Q_{cw} + W_{cw}(T_{ci} - T_{co})c_{pc}}{C_{cw}} \tag{6.37}$$

where C_{ct} and C_{cv} are heat capacities of tube and coolant inside the tube. W_{cw} is the coolant flow.

Finally mass conservation gives the relative condenser water mass

$$\dot{M}_{conr} = (W_{lo} + W_b - W_{con})/M_{ctot} \tag{6.38}$$

where W_{con} is the condenser outlet flow, calculated in the feed-water line module (cf. section 7) and M_{ctot} is the total mass capacity of the condenser.

6.6. Turbine trip and failures

In case of a turbine trip signal, generated from the controller and trip system (cf. section 9) the valves of the tubes leading steam to the HP- and LP-turbines and the reheater are closed unless a failure signal for one of the valves has been set by the user. In this case the valve remains open.

If a failure signal either on the HP-valve, the by-pass valve or the relief valve has been set the valve is stuck, i.e. the valve position remains in the fixed position it has when the failure signal is set.

If the failure signal to the safety valve is set the safety valve opens normally but leaks 0.5% of the maximum outlet flow on return to closed state.

All physical data and steady state values for the module are found in appendix A6.

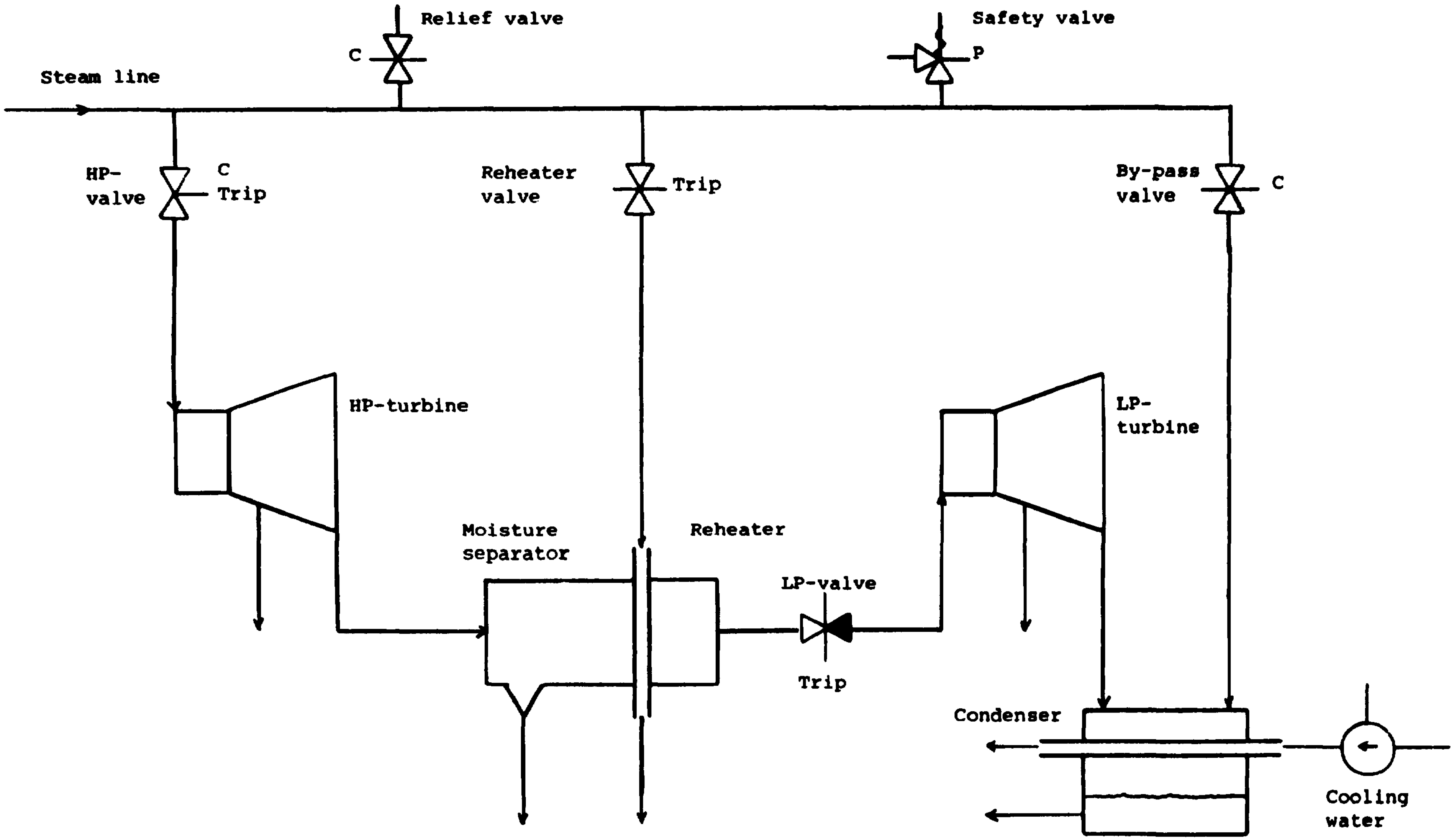


Fig. 6.1 Turbines and condenser.

7. FEEDWATER LINE

The feedwater line module is shown in Fig. 7.1 and comprises the condensate pump,preheater 1, the feedwater tank, the feedwater pump with the attached lubrication oil system and preheater 2. Also two non-return valves are present. The lubrication oil system is identical to the system on the primary side and is described in Section 8. The preheaters which are identical except for some parameters, are described in section 7.2.

It is assumed that water in the feedwater tank is saturated, i.e. the feedwater tank pressure is given from water temperature which in turn is determined from energy conservation.

7.1. Feedwater flow

Water from the condenser is pumped by the condensate pump through preheater 1 to the feedwater tank. The pump pressure upset is given from

$$\Delta p_{pc} = A_1 W_{con}^2 + B_1 W_{con} \omega_{cp} + C_1 \omega_{cp}^2 \tag{7.1}$$

where ω_{cp} is the controlled pump speed (cf. section 9) and W_{con} is the flow out of the condenser.

W_{con} is then determined from

$$p_{fwt} = p_c + \Delta p_{pc} - \Delta p_f \tag{7.2}$$

using (7.1). Here p_{fwt} is the feedwater tank pressure given from the tank water temperature

$$p_{fwt} = p_{sat}(T_{fwt}) \tag{7.3}$$

Δp_t is a constant friction pressure drop and p_c is the condenser pressure.

The feedwater temperature is raised from condenser temperature T_{con} to T_c in reheater 1 (cf. section 7.2) when it enters the feedwater tank.

Energy balance gives the tank water temperature

$$
\begin{aligned}
c_{ps}\rho_{fs}V_{fwt}l_{fWt}\dot{T}_{fwt} = {} & c_pW_{con}T_c + c_pW_{ph1}T_{ph1} \\
& + c_pW_{rh}T_{rh} + c_pW_{ms}T_{ms} \\
& + c_pW_{ph2}T_{ph2} - c_p(W_{fw}+L)T_{fwt} \\
& - c_p\rho_{fs}V_{fWt}T_{fWt}\dot{l}_{fWt}
\end{aligned}
\tag{7.4}
$$

where W_{1p}, W_{rh}, W_{ms}, W_{ph2}, W_{fw}, and L are drain flow from preheater 1, flow from reheater flow from moisture separator, flow from preheater 2, feedwater flow and a possible user specfied leak out of the tank. The flows from the preheaters are described in section 7.2. Flows from the reheater and moisture separator are calculated in the turbine module and given as input. c_p and V_{fwt} are specific heat capacities and volume of the feedwater tank.

The level of the feedwater tank is given from mass balance

$$\rho_{fs}V_{fwt}\dot{l}_{fwt} = W_{con}+W_{ph1}+W_{rh}+W_{ms}+W_{ph2}-W_{fw}-L \tag{7.5}$$

As for the condensate pump the feedwater flow W_{fw} is calculated from

$$p_{sg} = p_{fwt}+\Delta p_{pf}-\Delta p_f \tag{7.6}$$

where p_{sg} is the steam generator pressure and the feedwater pump pressure upset is given by

$$\Delta p_{pf} = A_2W_{fw}^2+B_2W_{fw}\omega_{fwp}+C_2\omega_{fwp}^2 \tag{7.7}$$

where ω_{fwp} is the controlled pump speed (cf. section 9). Feedwater temperature is raised to T_{fw} in preheater 2 before it enters the steam generator.

7.2. Preheaters

The preheater model is shown in Fig. 7.2. Primary side steam enters at pressure P_i with specific enthalphy h_i and condenses on the tube. The condensate is assumed to be saturated,i.e. the drain water temperature T_f is given from the pressure

$$T_f = T_{sat}(P_i) \tag{7.8}$$

A mean secondary side water temperature, T_{fm}, is calculated from inlet and outlet temperatures, T_i and T_o (cf. appendix D).

The heat transfer from steam to tube is given by

$$Q_{st} = K_{st}(T_f-T_t) \tag{7.9}$$

where T_t is the tube temperature. The heat transfer from tube to secondary side water is calcualted by

$$Q_{tf} = K_{tf}(T_t-T_{fm}) \tag{7.10}$$

Then energy balance gives the tube temperature, the steam inlet flow, W_g, and the secondary side water (feedwater) outlet temperature as

$$C_t\dot{T}_t = Q_{st}-Q_{tf} \tag{7.11}$$

$$W_g = \frac{Q_{st}}{h_i-h_{fs}(T_f)} \tag{7.12}$$

$$C_f\dot{T}_o = W_f c_{pf}(T_i-T_o)+Q_{tf} \tag{7.13}$$

where C_t, C_f, and c_{pf} are heat capacity of tube, water in tube and specific heat capacity of water. h_{fs} is the saturated water enthalpy. It is assumed that no drain water accumulation takes place, i.e. the drain outlet flow equals the steam inlet flow.

7.3. Failures

Failure signals on the two non-return valves can be set whereby the valves remain closed.

A pump flow fraction for each pump can be set, reducing the pump flow no matter the value of the controlled pump speeds.

Further a leak of water from the feedwater tank can be specified by the user.

Failures in the lubrication oil system may cause the feedwater pump to stop. In this case the feedwater flow will decrease exponentially with a time constant of 10 sec.

Physical data and steady state values for the module are found in appendix A7.

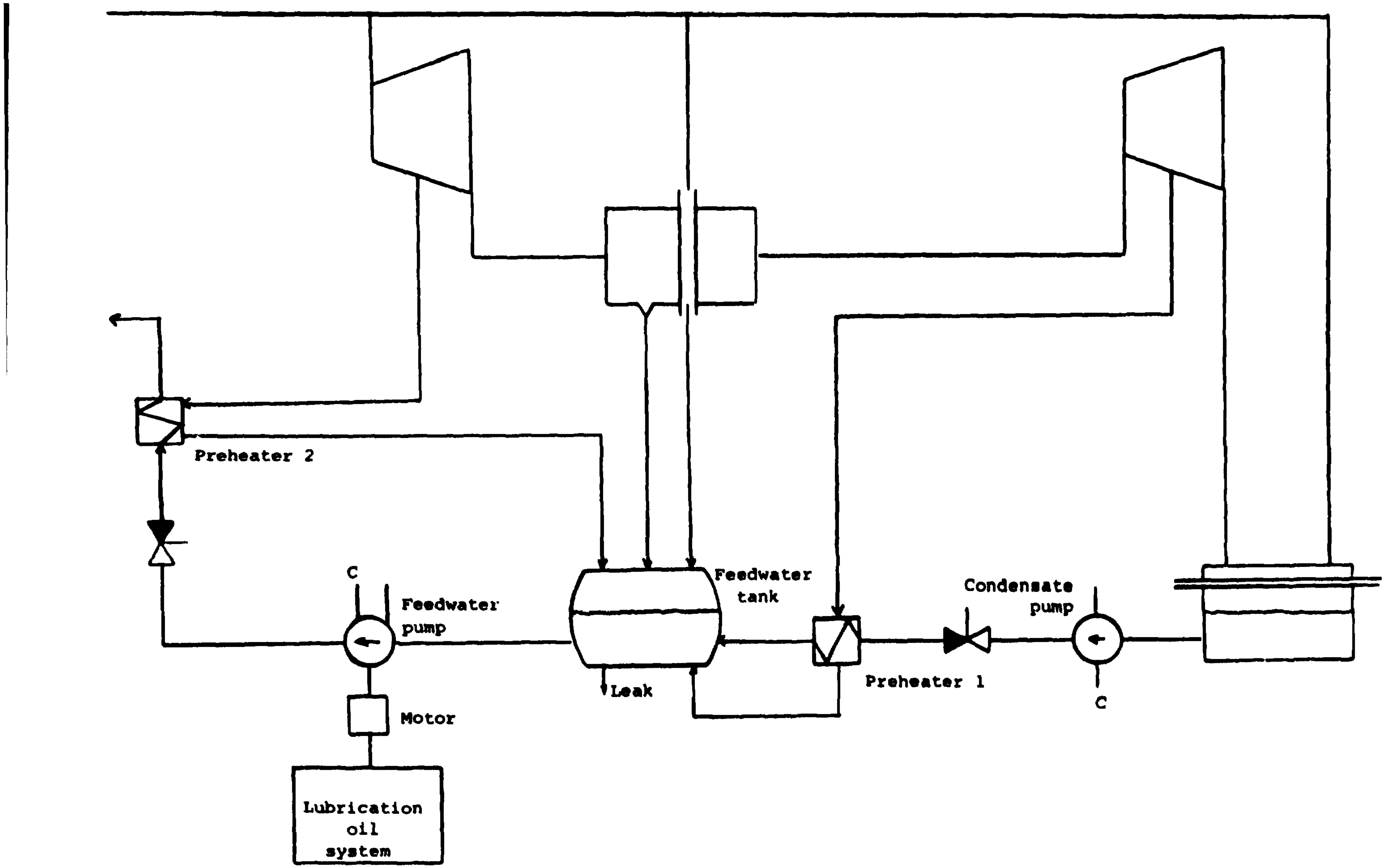


Fig. 7.1 Feedwater line.

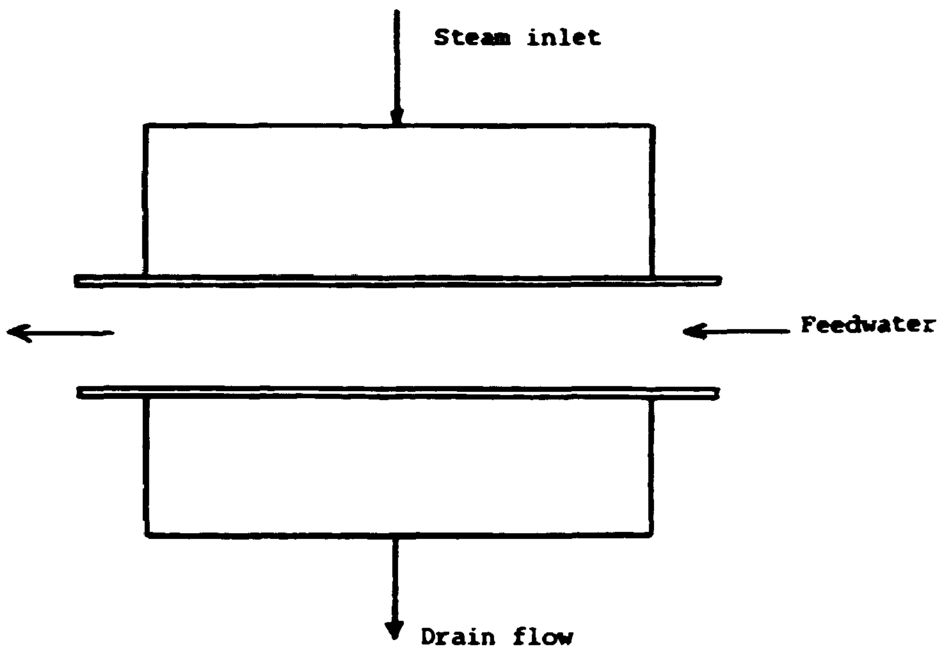


Fig. 7.2 Preheater.

8. LUBRICATION OIL SYSTEM

Two identical minor support systems are attached to the main energy system lubricating the bearings of the primary coolant and feedwater pump motors and maintaining conditions for pumping (cf. Fig. 8.1).

Lubrication oil from a tank is pumped through a filter to the pump motor. Oil is by-passsed to the tank in case of high pressure.

The by-pass valve position is calculated from

$$x_o = \begin{cases} o; & p_o < p_{o1} \\ \dfrac{p_o - p_{o1}}{p_{o2} - p_{o1}}; & p_{o1} \leq p_o \leq p_{o2} \\ 1; & p_o > p_{o2} \end{cases} \qquad (8.1)$$

opening lineary with increasing pressure in the interval from p_{o1} to p_{02}.

The oil flow W_o leaves the filter with an amount

$$W_o = k_1 S_p \qquad (8.2)$$

where S_p is the user specified pump speed. The oil pressure is given from

$$p_o = k_2 F_o W_m^2 \qquad (8.3)$$

where W_m is the inlet flow to the motor and F_o is a user specified friction factor. W_m is given from mass balance

$$W_m = W_o - W_{ob} \qquad (8.4)$$

where W_{ob} is the by-pass flow calculated from

$$W_{ob} = k_3 \sqrt{p_o}\, x_o \tag{8.5}$$

(8.3), (8.4), and (8.5) yields an equation for W_m

$$W_m = W_o/(1+k_3\sqrt{k_2 F_o}\, x_o) \tag{8.6}$$

from which p_o and W_{ob} can be calculated.

In case of low oil flow the motor will stop. This condition is determined by

$$W_o < \frac{W_o(\text{normal})}{2} \Rightarrow \quad S_m=0 \tag{8.7}$$

where S_m is the motor failure signal.

The equation for the relative mass of oil in the tank is

$$\dot{M}_o = -L_o/M_{otot} \tag{8.8}$$

where L_o is a possible user specified oil leak from the tank amd M_{otot} is the total oil content.

Equations (8.1), (8.6), and (8.3) form an algebraic loop which in most cases introduces numerical problems. In order to smooth out small oscillations in x_o, W_m, and P_o, these variables are calculated as a weighted sum of the actual value and the value from the previous integration step.

Physical constants are found in appendix A8.

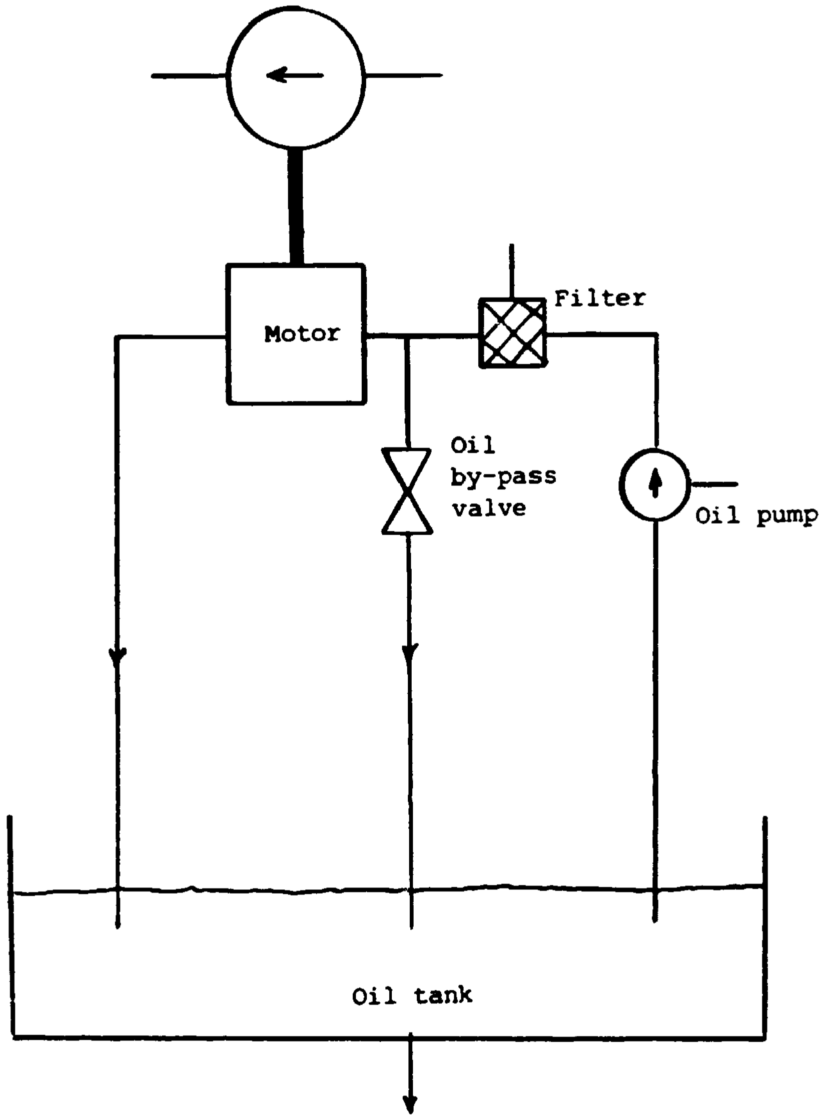


Fig. 8.1 Lubrication oil system.

9. CONTROLLERS AND TRIP SYSTEM

In all eight controllers are comprised by the model. The location of each controller and the device they act upon are shown in Fig. 1.1. Further the figure shows which components are sensitive to a generated trip signal. The way the individual components react to controller and trip signals are described in the previous sections. This section describes how the controller signals are calculated and what events cause a trip signal to be generated. Each controller is described in the following sections. However, two features are common to all controllers. Each controller consists of one or several proportional-integral (PI) controller components. A PI-controller is characterised by the transfer function

$$K(1+\frac{1}{\tau s}) \tag{9.1}$$

where K is the amplification constant and τ is the time constant. The equations for the PI-controller are

$$\begin{aligned} \varepsilon &= x_0 - x \\ \dot{z} &= \varepsilon/\tau \\ y &= K(\varepsilon+z) \end{aligned} \tag{9.2}$$

where x is the input signal, x_0 is the setpoint value, ε the error signal, z the integrated signal, and y the output signal.

Further many controllers consist of one or more 1. order lags with time constant τ characterised by the transfer function

$$\frac{1}{1+\tau s} \tag{9.3}$$

The equation for the lag is

$$\dot{y} = (x-y)/\tau \tag{9.4}$$

where x is the input signal and y is the delayed output signal.

9.1. Primary pressure controller, c_1

The diagram of the primary pressure controller is shown in Fig. 9.1. This is a pure PI-controller. The output signal controls the pressurizer spray cooling water valve, the proportional and back up heaters and relief valve 1. The pressurizer relief valve 2 is controlled directly by the primary pressure (cf. section 3). The pressurizer setpoint is specified by the user. Normal value is 155.1 bar.

9.2. Pressurizer water level controller, c_2

The diagram of this controller is shown in Fig. 9.2. The setpoint is calculated from a piecewise linear function of the reactor average temperature T_{avg}. The controller is of PI-type giving the speed of the volume control tank pump. An overriding action of water level on the pressurizer heaters is not shown on the figure. Below 15% level all heaters are disconnected and when the level is 5% above the reference level the backup heaters are turned on (cf. section 3).

9.3. Steam generator water level controller, c_3

The level controller diagram is shown in Fig. 9.3. The relative water level is calculated as

$$W_{lv} = (L_{SG}+1.18)/5.92 \qquad (9.5)$$

with a normal value of 0.66. Here L_{SG} is the level of the mixing chamber in the steam generator (cf. section 5). The setpoint is calculated from a piecewise linear function of relative nuclear power (cf. section 2). The input and setpoint signals go through 1. order lags, and the controller is of PI-type. The feedwater pump speed is calculated as a delayed sum of the PI-controller output and the deviation of relative flows out of and into the steam generator.

9.4. Reactor power controller, c_4

This controller of which the diagram is shown in Fig. 9.4 gives the reactor control rod speed. The reactor power is adjusted indirectly because this controller in fact controls the reactor average temperature, calculated as the mean value of the cold and hot leg temperature. This value is delayed and lead/lag compensated. The transfer function the lead/lag compensation is equivalent to the diagram of Fig. 9.5.a which gives the transfer function in terms of a simple integration (with time constant, τ_5, transfer function $1/\tau_5 s$) and a multiplication with τ_4/τ_5.

The setpoint for the average temperature is calculated as a piecewise linear function of relative HP-turbine inlet pressure (which is a measure of turbine power) and further sent through a 1. order lag.

A correction power mismatch between relative turbine and nuclear power is made. The equivalent diagram for the mismatch transfer function is shown in Fig. 9.5.b in terms of simple integration and multiplication. The power mismatch signal is sent through non linear and variable gains.

The error signal, corrected for power mismatch is transformed into control rod speed in the rod speed function of which the graph is shown in Fig. 9.5.c.

9.5. Turbine power controller, c_5

Figure 9.6 gives the turbine power controller diagram. The error signal is calculated from the sum of HP and LP turbine power and a user specified setpoint.

Both HP-valve position and flow are calcualted together here thereby saving evaluations of the non-linear function, F_V. The calculation of HP-valve flow also involves the steam line pressure.

9.6. By-pass valve, secondary relief valve and feedwater tank level controllers, c_6, c_7, c_8)

All controllers are of simple PI-type (cf. Fig. 9.7. a,b,c). The by-pass valve and relief valve controllers have fixed setpoints whereas the feedwater tank level setpoint is specified by the user.

9.7. Trip system

Conditions for reactor trip and turbine trip are listed below. Because a reactor trip will cause a turbine trip and visa versa only one trip signal is generated. During non-trip periods the trip signal equals zero. When one of the trip conditions is met the trip signal will take a non-zero value according to the list below. The actions taken by various components of the plant are described in sections 2 and 6. A non-zero trip signal will override the rod speed controller (c_4) output, generating a signal for control rod insertion with maximum speed.

Conditions for trip:

	Trip signal
Turbine:	
High steam generator level (> 79.4%)	1
High condenser level (> 70%)	2
High condenser pressure (> 0.3 bar)	3
Reactor:	
High nuclear power (>109%)	4
Low primary flow (< 84%)	5
Primary pressure out of range (range: 135.0-165.4 bar)	6

High pressurizer level	
(> 92%)	7
Low steam generator level	
(< 19.9%)	8
Manual scram signal	
(set by user)	9

9.8. Controller failures

Two types of controller failures are possible for each individual controller.

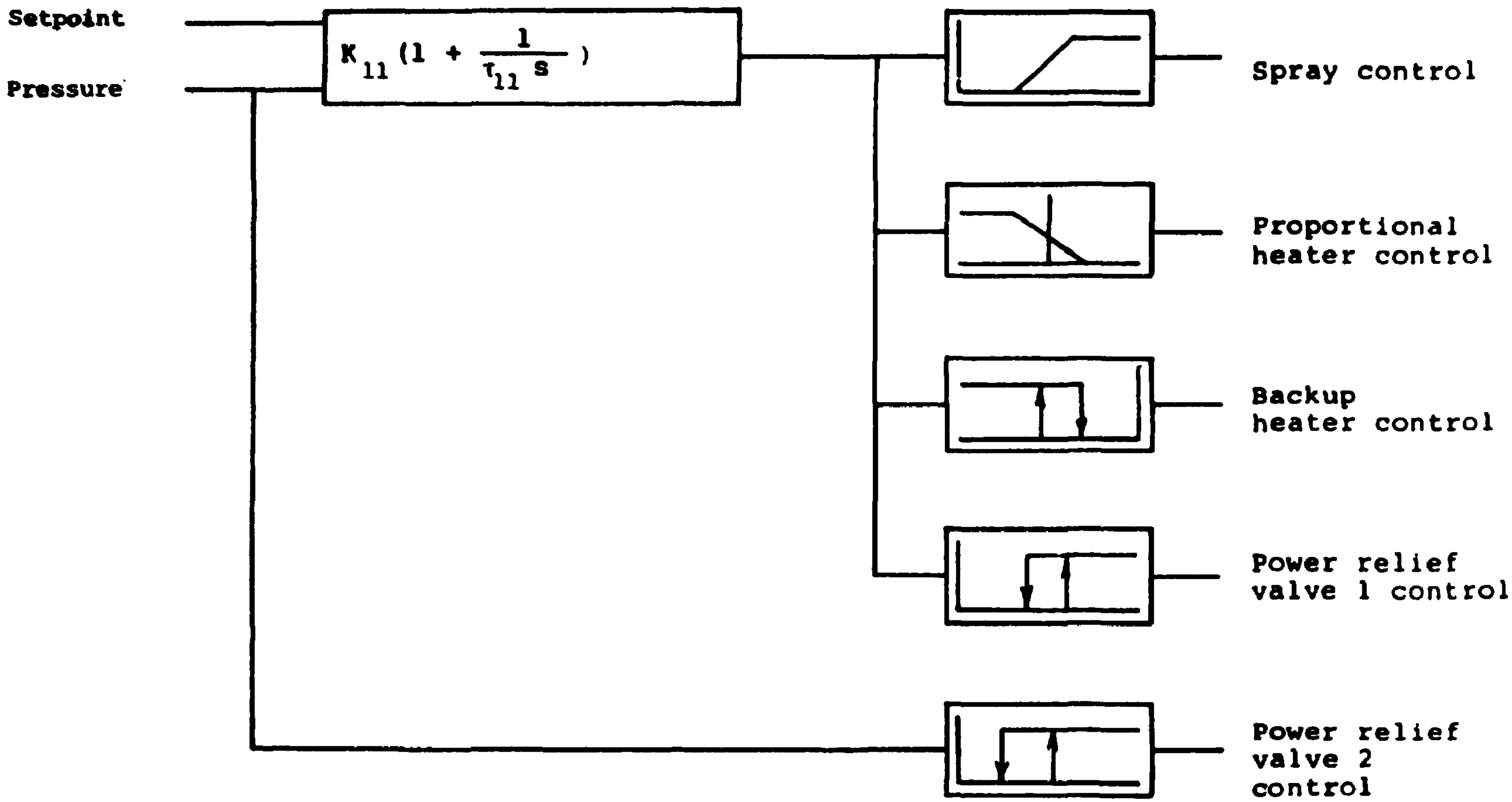
A controller may be set to drift; i.e. the controller output signal will start to drift either to its maximum or minimum value. The drift will start when the failure signal for the particular controller is set, continuously increasing or decreasing the output signal lineary to the maximum or minimum value within at most 30 seconds. If the drift signal is set, the drift will take place no matter what input the controller recieves.

A controller may also be blocked; i.e. the controller output signal remains constant at its value when the failure signal is set, no matter the input to the controller.

When either one of the two possible failure signals for a particular controller is set, integral signals of the controller are kept constant.

For further details of failures and disturbances c.f. section 10. Please be aware of the difference between a failure signal to a controller and a possible failure signal to the device upon which the controller is acting.

Controller data and steady state values are found in appendix A9.



<u>Fig. 9.1</u> Primary pressure controller. c_1.

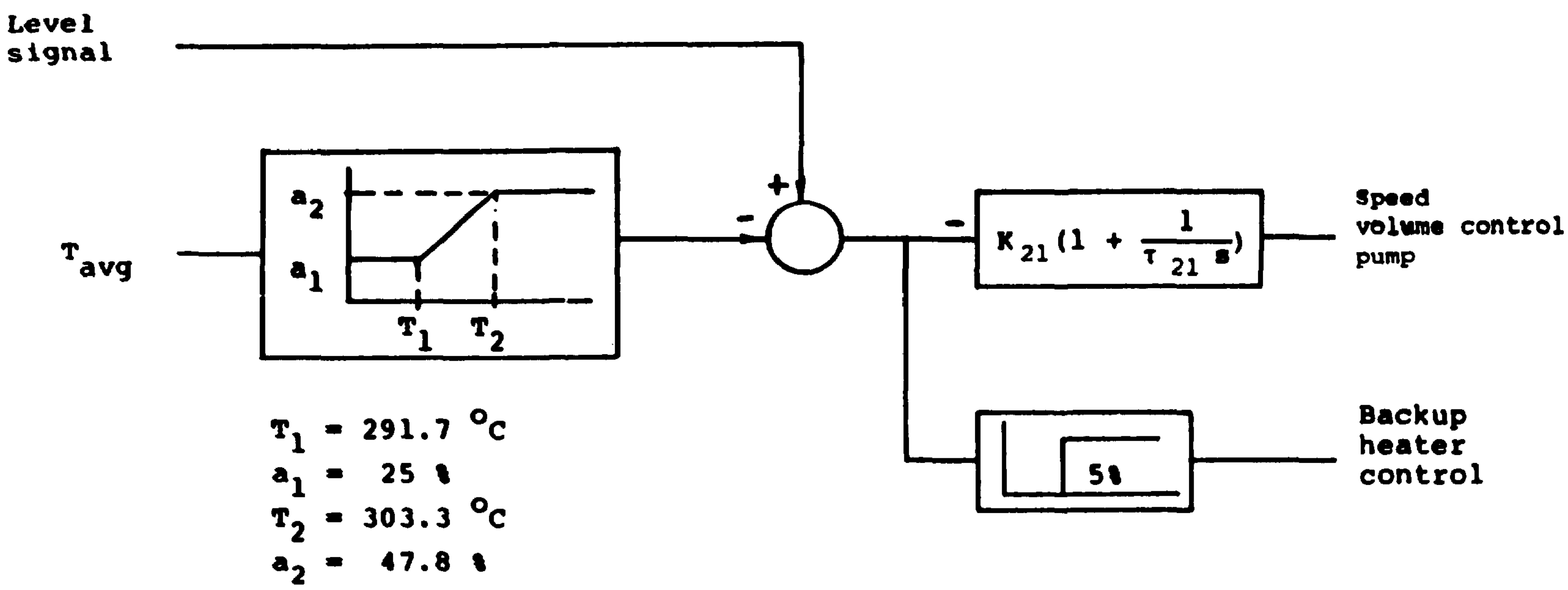


Fig. 9.2 Pressurizer walet level controller. c_2.

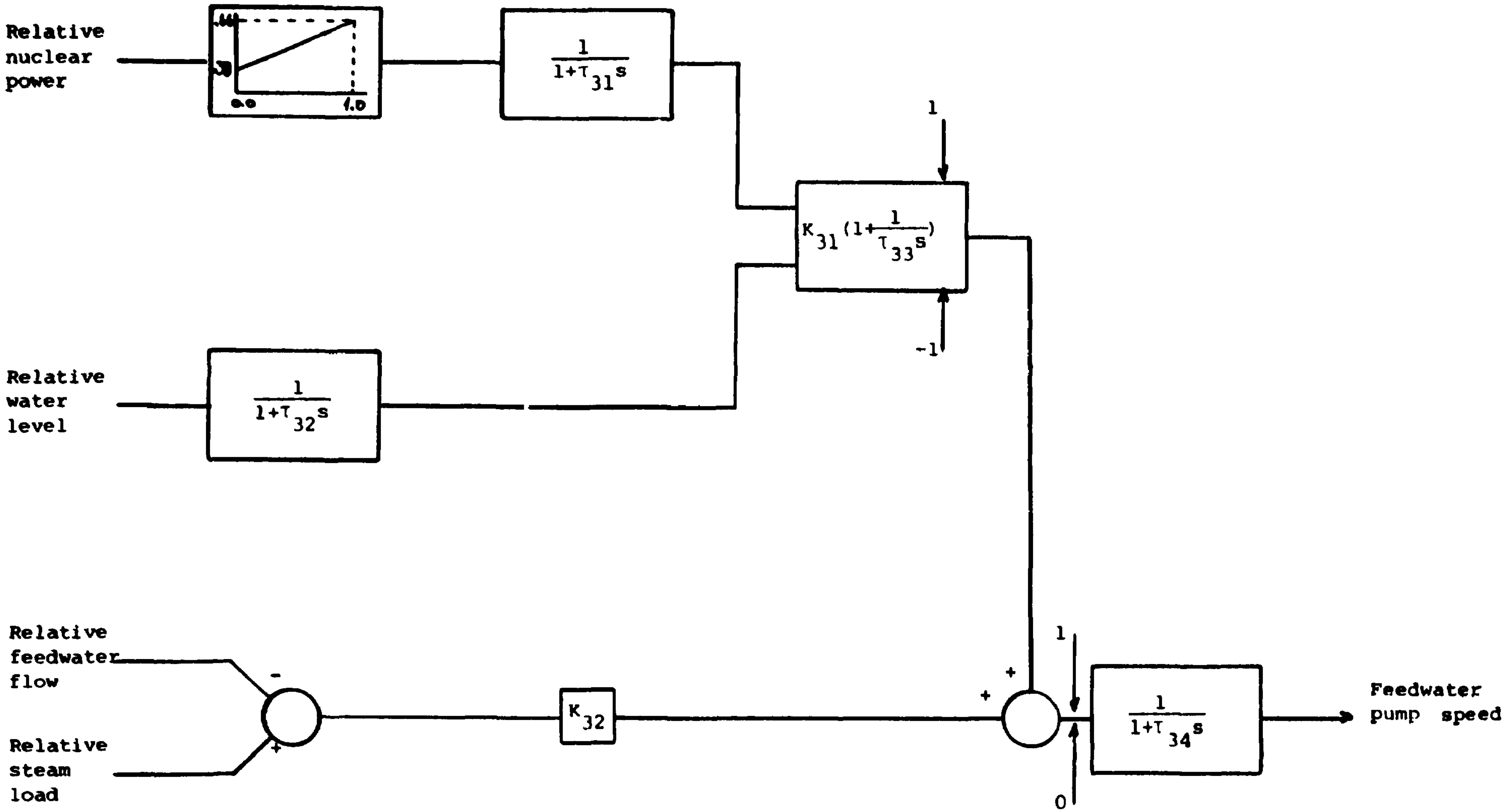


Fig.9.3 Steam generator water level controller, c_3.

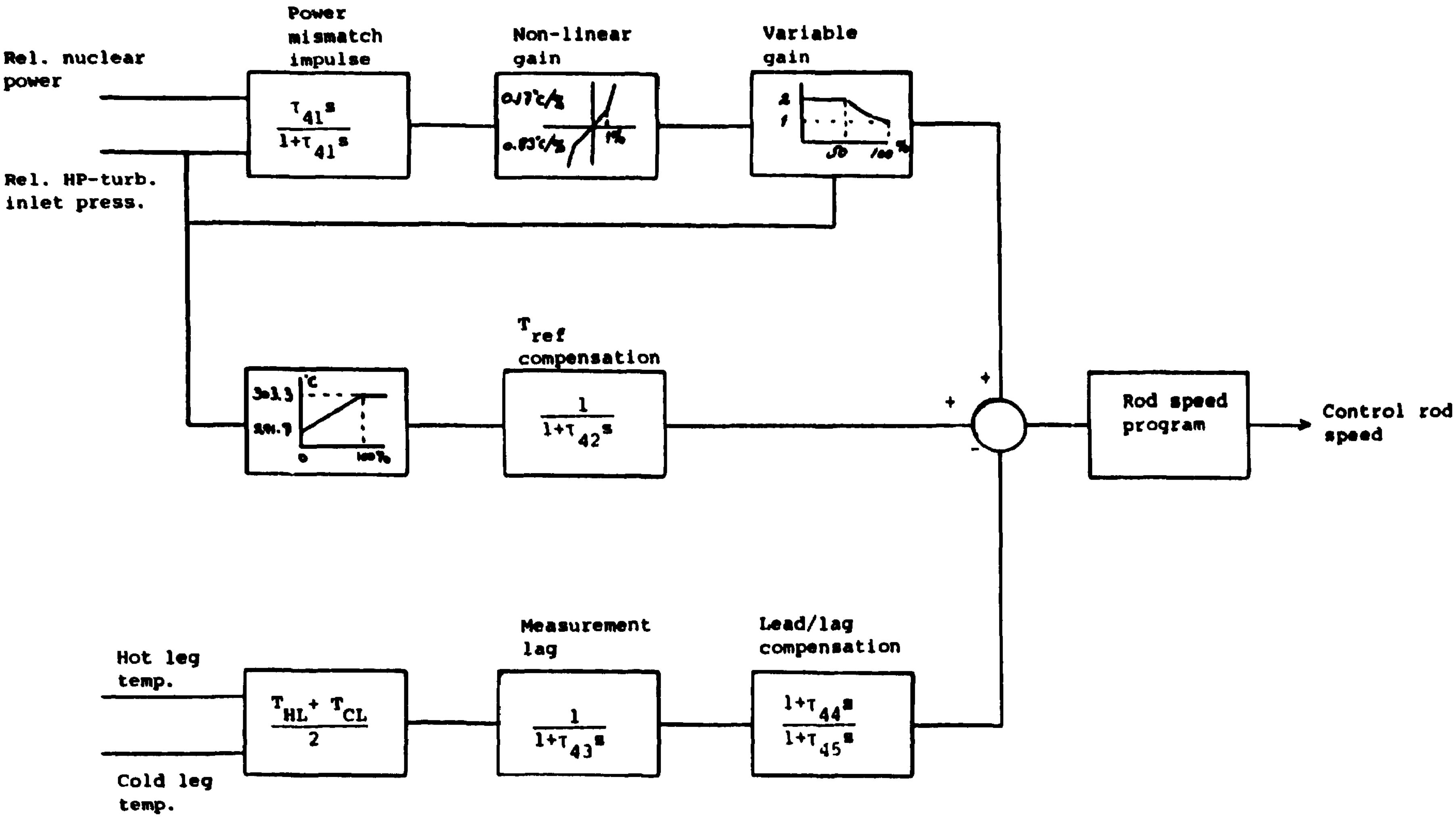


Fig. 9.4 Reactor power controller, c_4.

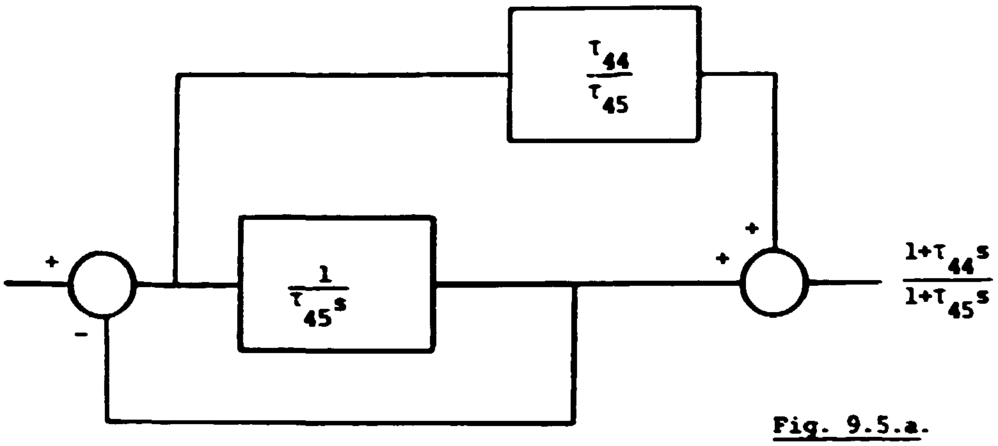


Fig. 9.5.a.
Lead/lag.

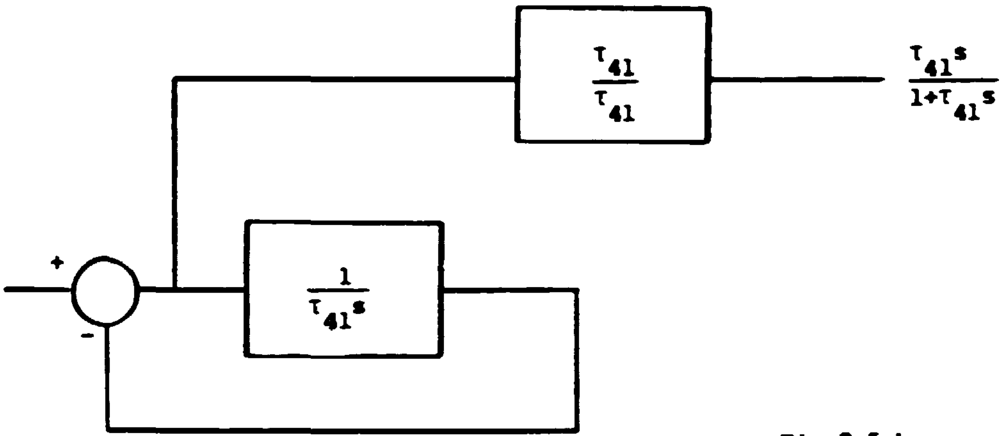


Fig.9.5.b.
Mismatch

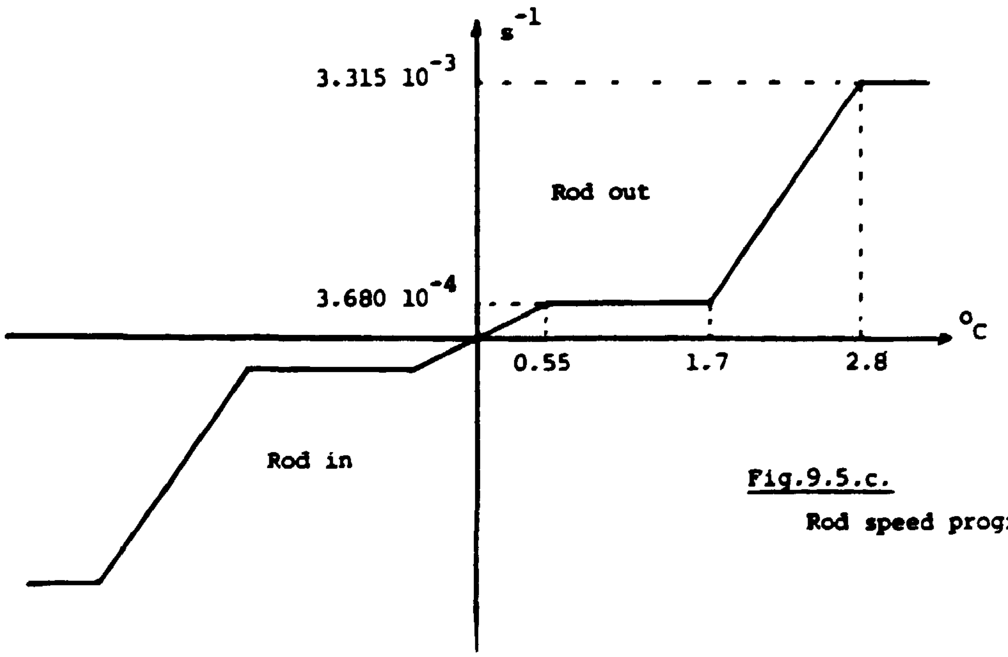


Fig.9.5.c.
Rod speed program

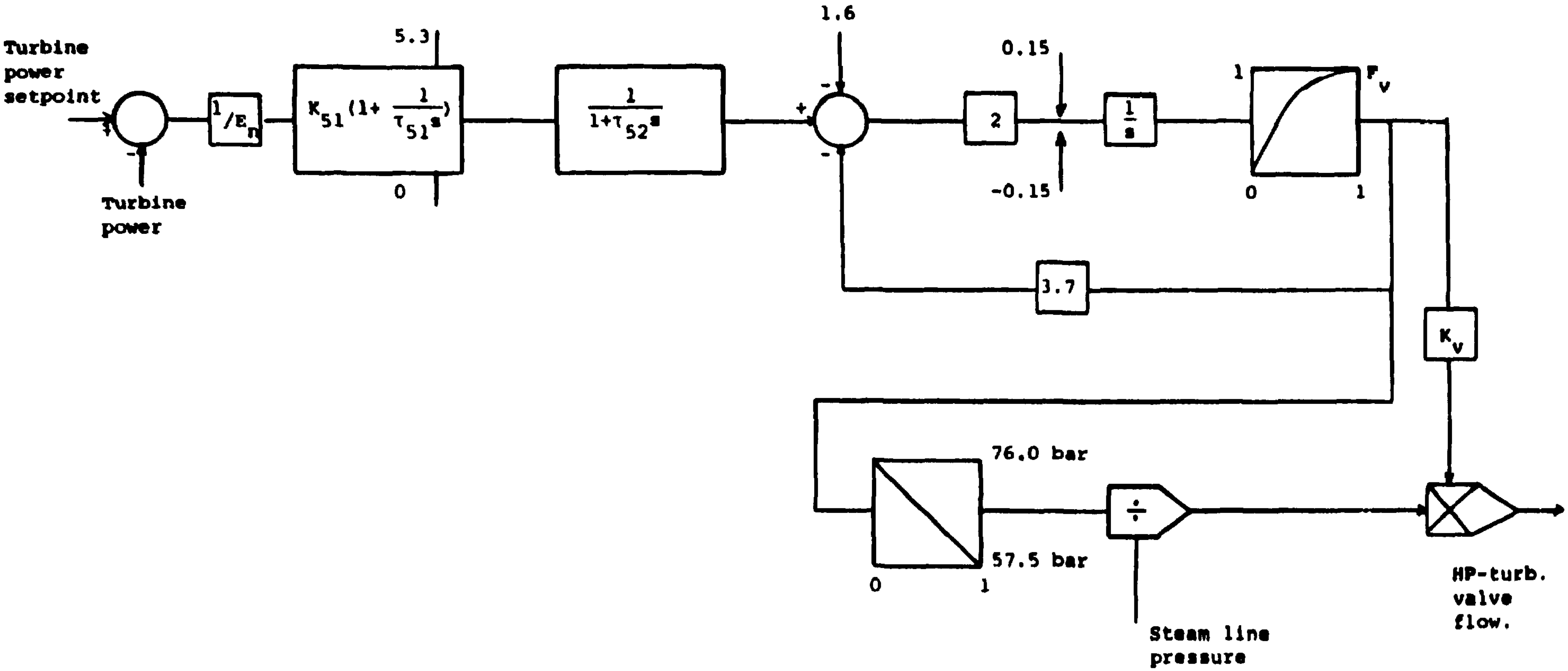


Fig. 9.6. Turbine power controller, c_5.

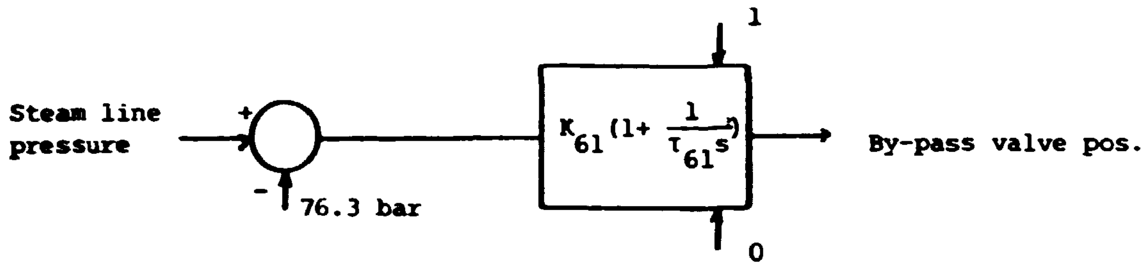


Fig.9.7.a. By-pass valve controller, c_6.

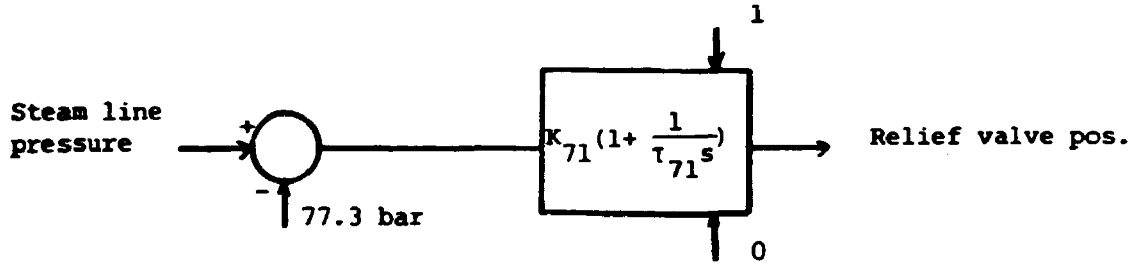


Fig.9.7.b. Relief valve controller, c_7.

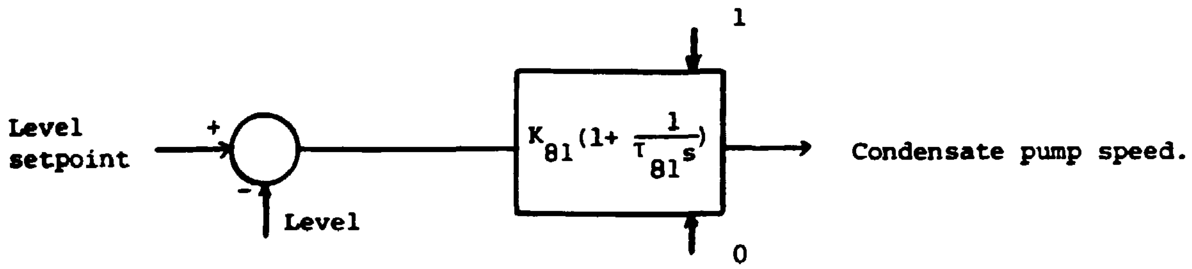


Fig.9.7.c. Feedwater tank level controller, c_8.

10. THE SIMULATOR

10.1. General description of the simulation system

The PWR power plant model has been written as seven modules to be connected to the general purpose simulation system DYSIM, developed at the Department of Energy Technology at Risø (cf. Christensen et al. 1986).

In this simulation system a model of a plant is composed as a series of modules. Each module corresponds to a logical and functional unit of a plant. The modules are written as a mixture of simulation language, macro calls, and ordinary fortran 77 statements. Each module can run and be tested independently.

A library of submodules, representing various technical standard components (e.g. heat exchangers, pumps, valves, controllers) may be used building a module. The advantage of the library is that each submodule, possibly characterised by a set of parameters, is a well tested code which may be used at several places in the model by a simple macro call.

Two precompilers have been used to create the fortran 77 code of the model (cf. Kofoed, 1987). Precompiler 1 processes each module, incorporating the proper submodules from the library whereas precompiler 2 connects the individual modules to an entire fortran 77 code.

10.2. Structure of the model

The structure of the entire simulation system is shown in Fig. 10.1. The mathematical model of the PWR-power plant consists of 7 modules. These modules are:

- controllers and tripsystem (CT)
- reactor and primary loop (RE)
- pressurizer (PR)
- containment activity (AC)
- steam generator (SG)
- turbines and condenser (TU)
- feedwater line (FW)

The modules have been described in the previous sections.

In the modules differential quotients of state (integration variables) and algebraic variables are calculated. However, this can only be done using values of variables from other modules. The connecting system, CON, which is to be regarded as a module itself,sets up the necessary input variables for each module on the basis of state and algebraic variables from other modules. Further the connecting system directs differential quotients to DYSIM which performs the integration and error control. DYSIM also administrates the output as specified by the user.

The simulation system uses four kinds of variables for each module:

- input variables } input
- parameters
- state variables } output
- algebraic variables

The input variables are set up internally by the connecting system as described. The parameters are constant input specified by the user in the input file. The state and algebraic variables are the calculated variables which together characterise the state of the system.

The list file (cf. appendix B) holds names of all variables of the different type for each module. The list file is read by DYSIM, but should also be consulted by the user to identify the variables. Each variable is described by dimension and a short explanation. Of special interest are the state and algebraic variables since these variables constitute the potential output.

Also the parameters of the connecting system are of interest because the user specifies these values in the input file in order to generate various transients. The list file is a text file and copies of the file can be printed.

The input file which holds initial conditions, parameter values, and commands for the simulation systems is described in the next section.

Two output files are generated by DYSIM. The printfile holds a table of values of user specified (state or algebraic) output variables at specified time steps. The print file is a text file which can be printed whereas the plot file is a binary copy used by an auxiliary plot program to draw graphs of the calculated transients.

The list file holds the obligatory DOS-name LIST.SEQ and the print file is given the name PRINTER.DAT. The input file can have any DOS name with extension .SEQ. The plot file will be given a user specified name with extension .UNF. All files must/will remain under the same directory as the executable code.

10.3. Input file and possible transients

A large variety of disturbances and failures in the plant may be simulated. All disturbance and failure signals are given as parameters of the connecting system. Values of these parameters can be specified in the *DATA-field of the input file. An example of an input file is found in appendix C. Parameters of the connecting system all have name extension .CON and appears in lines 1500-9600 of the shown input file together with a value. The value may be changed by a text file editor as described below in order to set the parameter for a simulation run. In Fig. 10.2 the corresponding device to each parameter is shown.

The parameters are divided into two groups: disturbances and failures. Disturbances may be time dependent whereas failures signals are active when the parameters are set.

Disturbances: (cf. appendix C, lines 2200-3800)

Primary pressure setpoint:	PP.CON
Turbine power setpoint:	E.CON
Feedwater tank level setpoint:	LFWT.CON
Inlet coolant temperature:	TCI.CON
Lubrication oil friction parameters:	
Primary side:	FOP.CON
Secondary side:	FOS.CON
Primary pump speed:	SPPP.CON
Cooling water pump speed:	SPCWP.CON

These parameters can be changed lineary as a ramp function from the values Y.CON to Y.CON + DY.CON in the time interval T1.CON to T2.CON (cf. Fig. 10.3), e.g. if the turbine power setpoint is to be descreased lineary from 458.0 MW to 400.0 MW in the time interval [10,20] sec.; set DE.CON = -58.0 in the input file. If another time interval is desired change the values of T1.CON and T2.CON in line 1500. Values of the above parameters in the input file correspond to steady state, i.e. only the deviations (e.g. DE.CON) should be changed. The values of T1.CON and T2.CON are common to all disturbances. Equal values of T1.CON and T2.CON cause a step change. Values of DFOP.CON and DFOS.CON above 9 make the pumps to stop.

Failures: (cf. appendix C, lines 4500-9600)

Controller block signals (lines 4500-4700)   B1.CON-B8.CON

Normal values are 0. If +1 or -1 is specified instead the controller output will drift to the maximum or minimum value respectively within at most 30 seconds after the parameters has been set. If 2 is specified the controller is blocked, i.e. the controller output signal remains fixed at its value when the block signal is set.

Valve functions (lines 5200-5800) FPSV.CON-FCV.CON

Normal values are 0; any other value means a failure. If a failure on a safety valve is set the valve opens normally but leaks 0.5% of the maximum outlet flow on return to closed state. A failure signal on any controller or trip driven valve causes the valve to remain fixed at the valve position it had when the failure signal was set. The non-return valves remain closed when a failure signal is set.

Valve positions XRHV.CON and XLP.CON

Reheater and LP-turbine valve positions. Allowed interval [0,1] with normal value 1. The value of the parameter corresponds to a fraction of normal non-trip flow through the valve.

Volume control tank inlet flow WLED.CON

Specified in kg/sec. Normal value is 2.8 kg/s

Leaks (lines 7100-7800) LPG.CON-LLOS.CON

Specified in kg/sec. Normal value is 0 kg/s.

Pump flow fractions FFWP.CON, FCP.CON, FVCP.CON

Allowed interval [0,1] with normal value 1. The value of the parameter corresponds to a fraction of normal flow from the three controlled pumps.

Pump speeds SPLOP.CON, SPLOS.CON

Normalized pump speeds of the lubrication oil pumps.
Normal value 1.

Switches (lines 9100-9200) SRODM.CON-SBH.CON

Normal value 0. Any other value corresponds to an off-state of the switch.

Manual scram signal MSCRM.CON

No scram corresponds to 0. Any other value causes the ractor to trip within 0.3 seconds after the parameter has been set.

The rest of the *DATA field (cf. appendix C, lines 10200-11300) gives parameter values to other modules. These values should not be changed by the user.

Output specifications

Values of state - and algebraic variables can be written on the plot - and printer files at specified times. The print intervals are specified in line 12200 of the shown input file (appendix C). The first number INT-1 gives the frequency of print out in the time interval from 0 sec. to PTIME-1, then the frequency is changed to INT-2 in the time interval PTIME-1 to PTIME-2. After PTIME-2 output is written with frequency INT-3. In the example of appendix C data is written every second for the first 10 seconds, then every 0.5 second in the time interval 10 seconds to 200 seconds. After 200 seconds output is written every 5th second.

After the print interval specification a list of the desired state and algebraic values to be printed follows. Remember that a variable name has the module name as extension. Lines 12300-13400 give an example of an output list. The list may be changed by the text file editor. Notice that the indicated columns must be maintained. The output list is terminated by PRNT.END.

Also a name of the plot file must be specified. In the example of appendix C the plot file is named F2 and the file will get the DOS-extension .UNF. Notice that an existing plot file with the same name will be overwritten.

A header for graphs and tables may be specified. In the example the header is

"PWR POWER PLANT SIMULATOR"

as shown in line 14700.

The last number of interest to the user is the SERVER-time, i.e. the 5th number in the *CHCK-field (line 15300 in the example). This number gives the time when the simulation process is temporarily stopped. For further details see the following section.

The rest of the input file is of no direct interest to the user. The numbers in the *INCO-field give initial values of all state - and algebraic variables. These values correspond to a steady state of the system, i.e. any simulation will start from this condition. The *INCO-values should not be changed by the user. For further details of the input file the user is referred to Christensen et al. 1986.

10.4. The SERVER

A simulation run can be interrupted at any time by pressing the keys, Ctrl and C at the same time. This causes the simulation system to go into "SERVER"-mode. In the SERVER-mode you can ask for values of any state or algebraic variable by writing the variable name. Also the values of parameters can be changed by writing the parameter name. In this way a disturbance or failure can be set (or reset) during the simulation. To continue the simulation with possibly new parameter values, write C followed by a number of seconds. After the specified time interval the SERVER will report itself again. If on the other hand the simulation is to be stopped, type EXIT.

There are two ways to run a simulation:

a) Set up the input file in order to generate the desired transient and write a large number in the *CHCK-field for the SERVER-time. At this time the SERVER reports itself.

b) Set up the input file corresponding to no disturbance or failure (as shown in appendix C), and a few seconds for the SERVER-time. When the server reports itself, you can set the parameters corresponding to the desired transient and continue the simulation. Be aware that the ramp function start time T1.CON should be larger than the SERVER-time in order to avoid discontinuous disturbances.

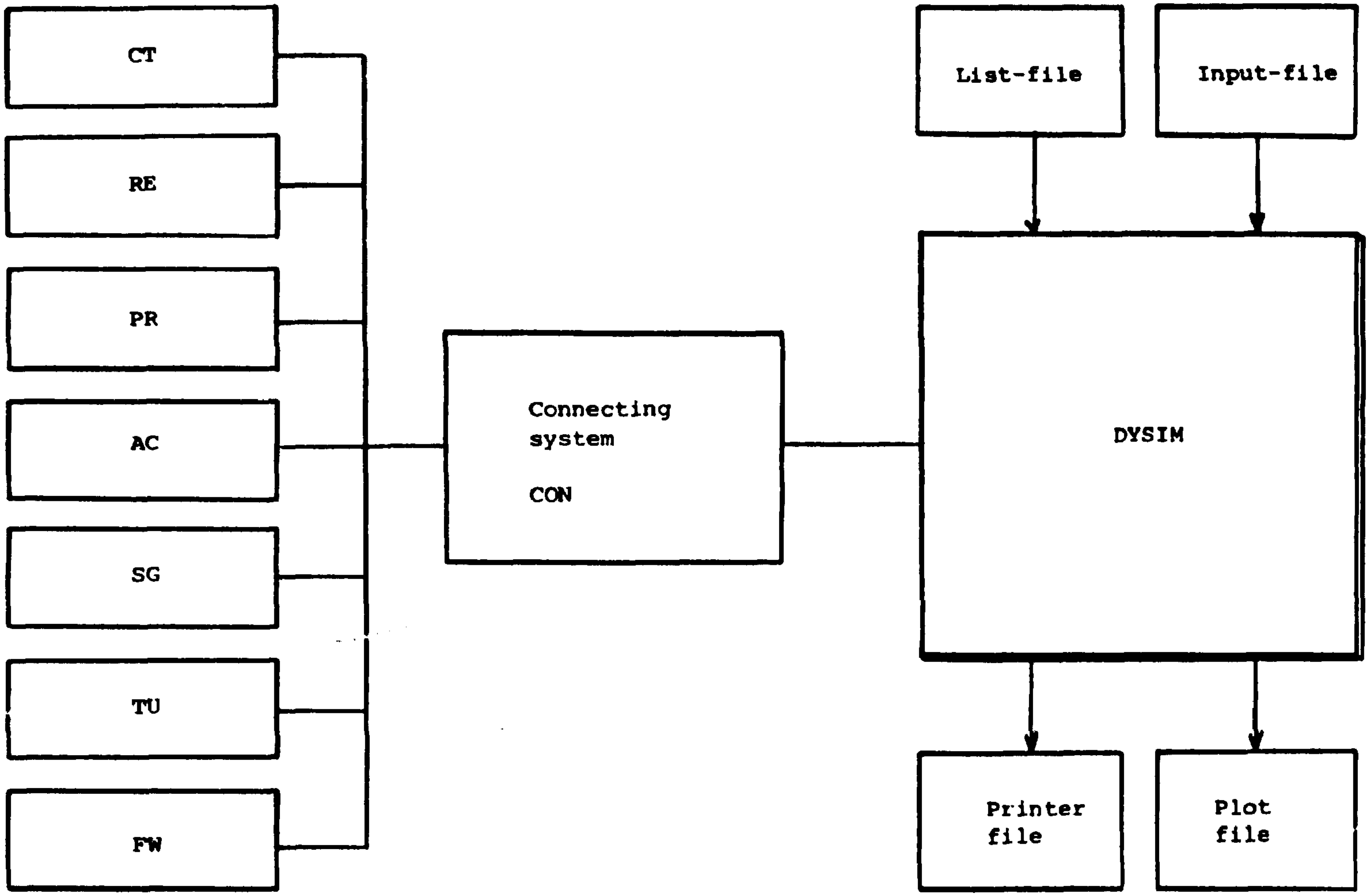


Fig. 10.1. Structure of the simulator.

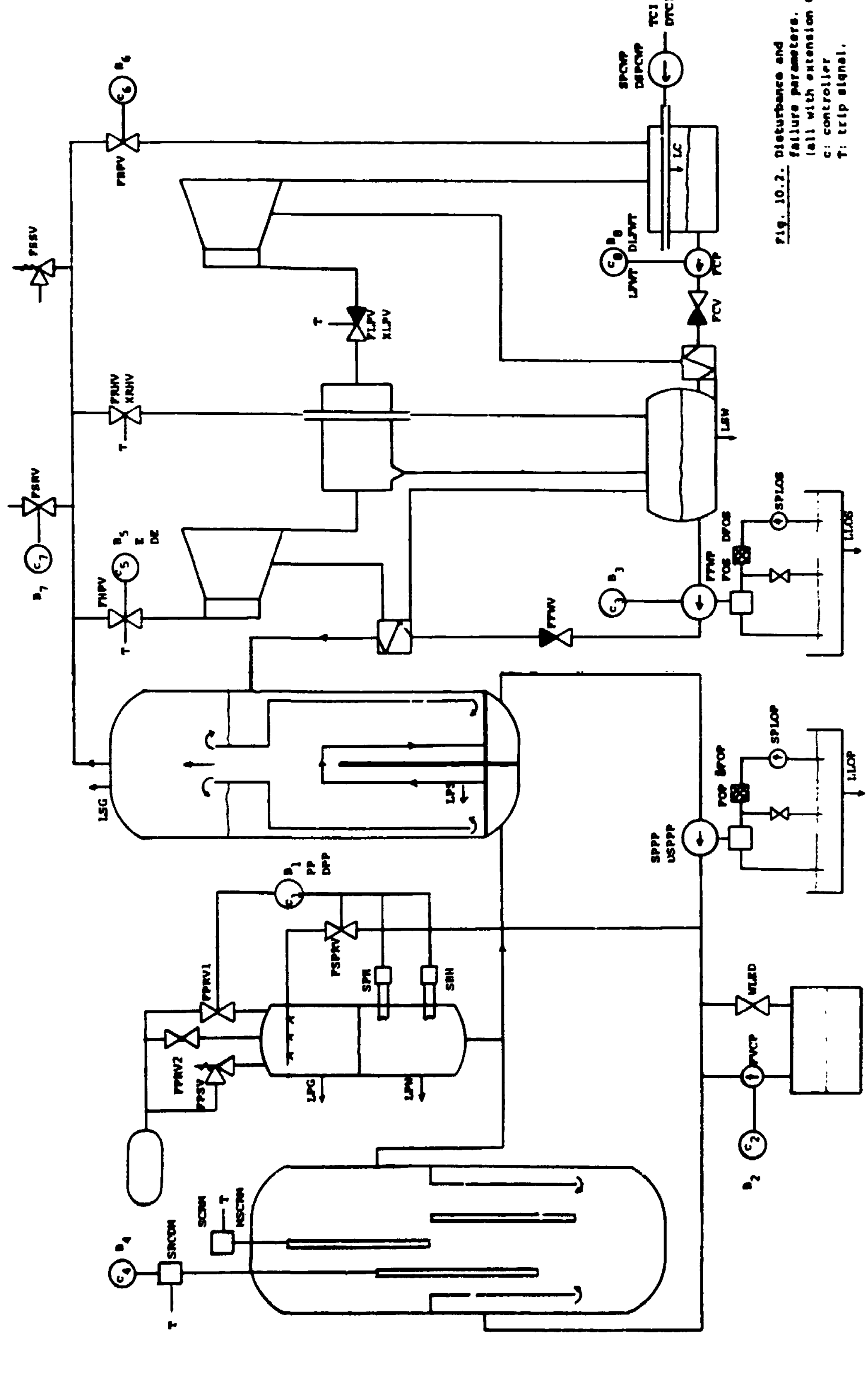


Fig. 10.2. Disturbance and failure parameters. (all with extension CON). C: controller T: trip signal.

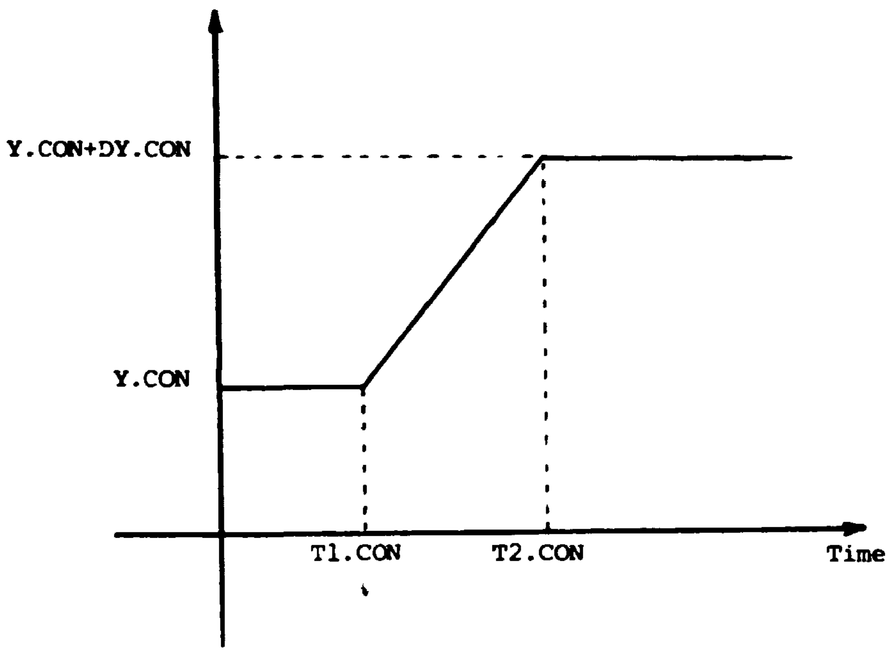


Fig. 10.3. Ramp-function.

11. CALCULATION EXAMPLE

A single transient example is given mainly to illustrate how to set up the input file, run the simulation model and examine the results.

In this example the lubrication oil friction factor FOS.CON in the secondary side oil system is increased from 1 to 10 as a ramp function in time interval 10 seconds to 100 seconds. In order to generate this transient the input file of appendix C is changed in the following way: T2.CON = 100; DFOS.CON = 9, SERVER-time 200. Alternatively the input file can be used as it appears in appendix C (no disturbances or failures). When the server reports itself at 10 seconds the two above parameter values are set and the simulation is continued for 190 seconds (C190).

In this transient the simulation will not go on to 200 seconds because the model will run out of its validity domain, due to the very drastic events in the plant. In this case DYSIM terminates by itself with a "stop by call term"-message on the screen and in the PRINTER.DAT file. However, the output is stored in file F2.UNF and PRINTER.DAT.

The auxilliary DYSIM-plot program (PLOT.EXE) is used to visualize how the output variables change.

The lubrication oil pressure POS.FW increases due to the increasing friction (cf. Fig. 11.1). When pressure is above 2 bar the oil by-pass valves opens and the oil flow WOS.FW to the motor decreases.

When the oilflow is below 0.5 kg/s the feedwater pump stops and the feedwater flow WFW.FW decreases exponentially (cf. Fig. 11.2), whereby the relative condenser mass MCONR.TU increases.

The steam generator level L.SG decreases (cf. Fig. 11.3) because no feedwater enters. When the level is below zero, a trip signal (TRIP.CT = 8) is generated.

The steam generator pressure P.SG and the downcomer water temperature TD.SG increases due to lag of coolant (Fig. 11.4)

The turbine power E.TU remains constant until the trip occurs (Fig. 11.5). When the HP-turbine valve closes the steam generator pressure increses abruptly and a by-pass steam flow WB.TU is dumped into the condenser.

The increased secondary side temperature causes a drop in the heat transfer QSG.SG in the steam generator (cf. Fig. 11.6). After the trip the very high pressure causes a further rapid drop in heat transfer because the evaporation decreases. The decreasing heat transfer implies an increased average reactor temperature TAVG.RE until the trip when the reactor power vanishes.

In order to reduce the average temperature the control rod is moved inward, (CR.RE) and the relative nuclear power QNUCL.RE is reduced (cf. Fig. 11.7). When the trip occurs the reactor power vanishes and the control rod is moved inward with maximum speed.

The simulation was stopped because the thermodynamic functions used in the turbine model are evaluated outside their range.

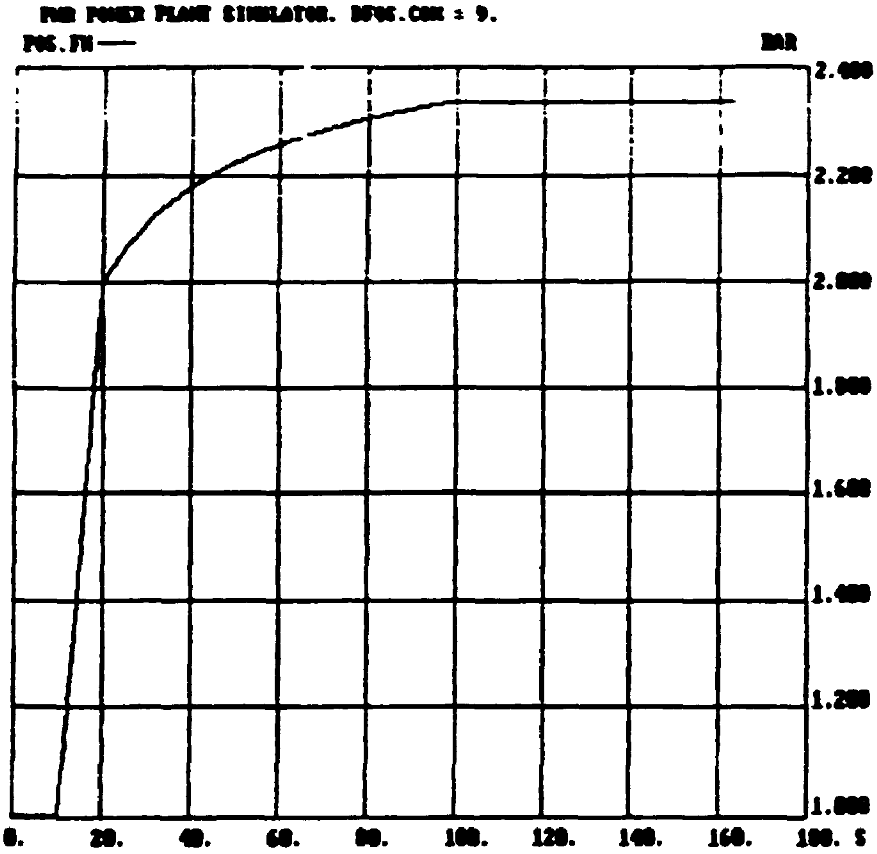
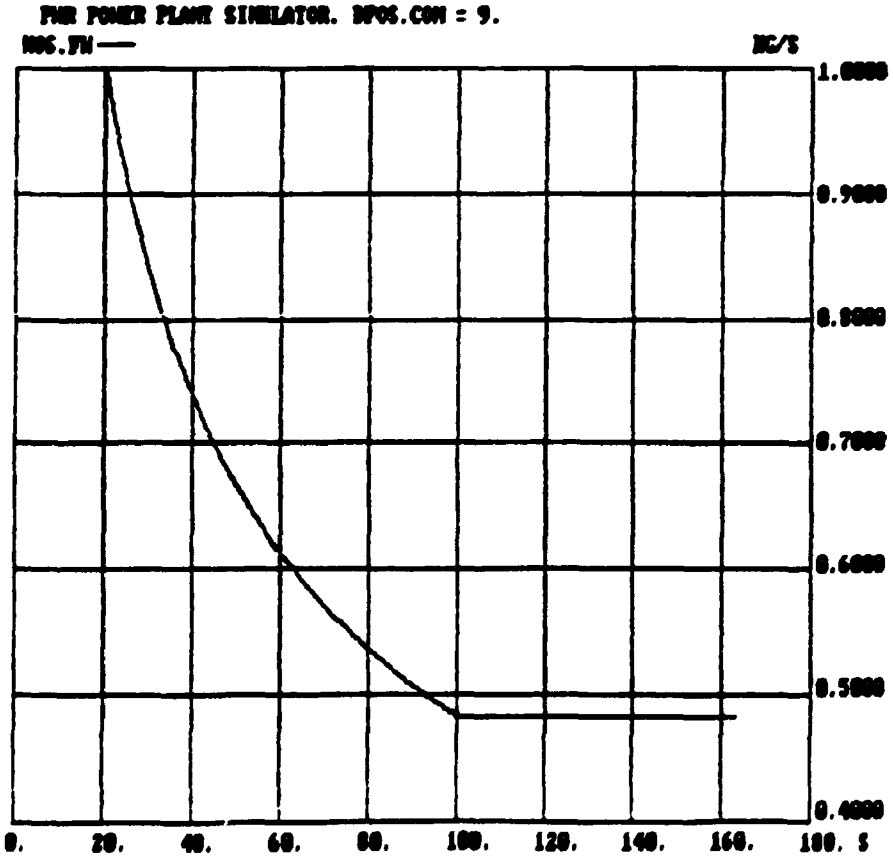


Fig. 11.1. Oil pressure and oil mass flow.



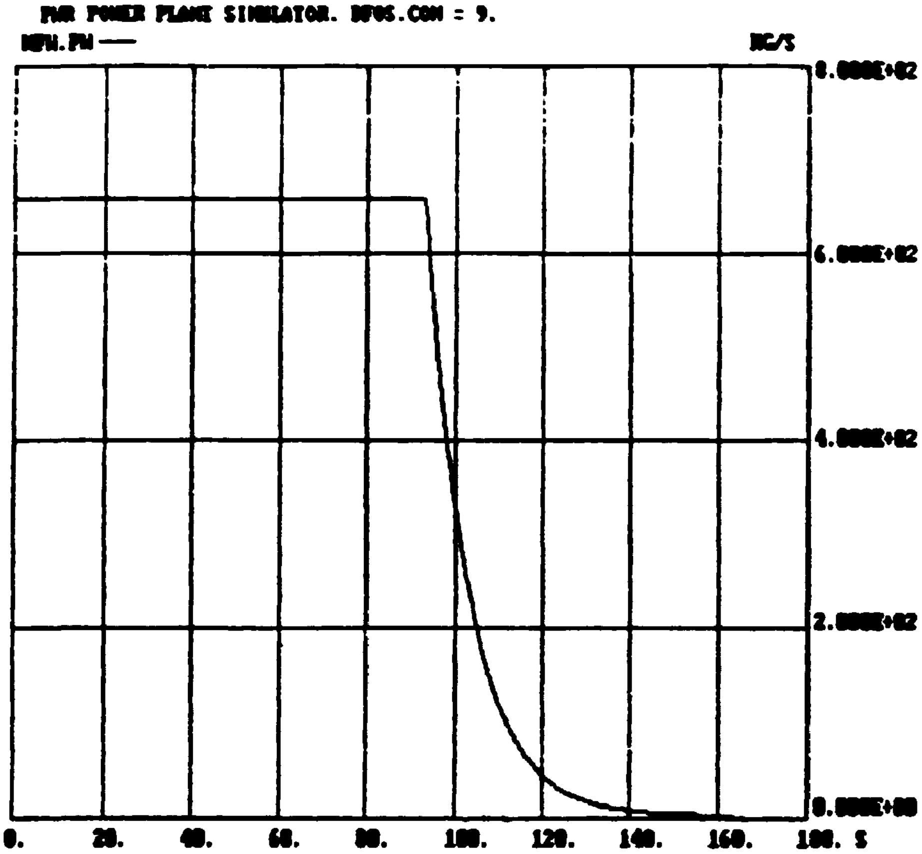
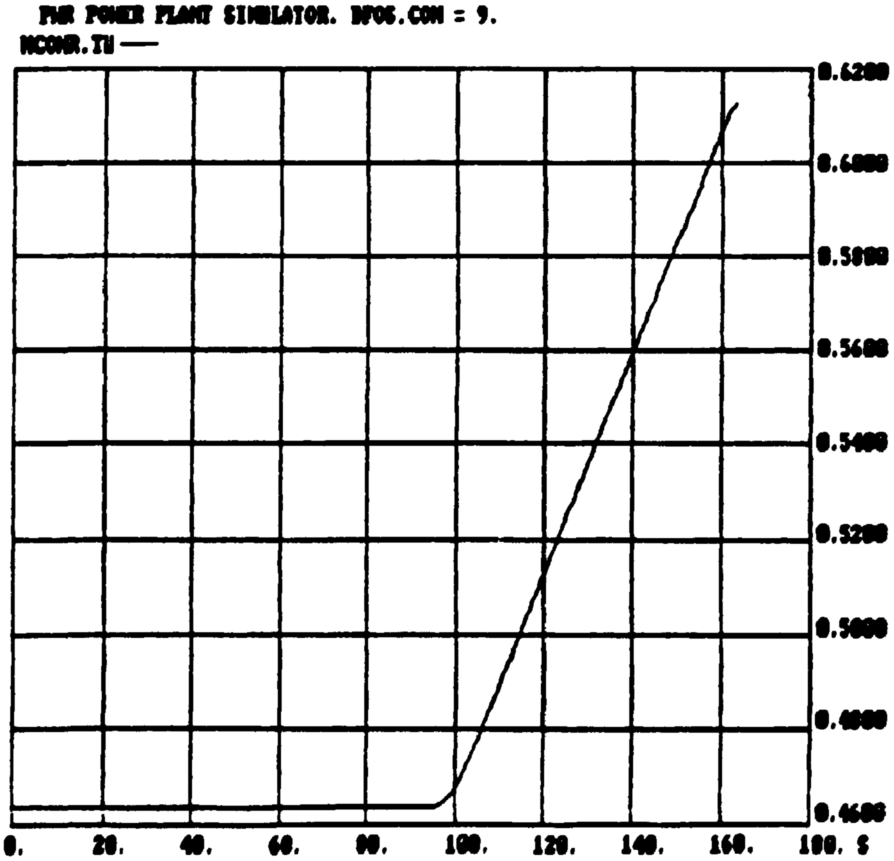


Fig.11.2. Feedwater flow and
relative condenser water mass.



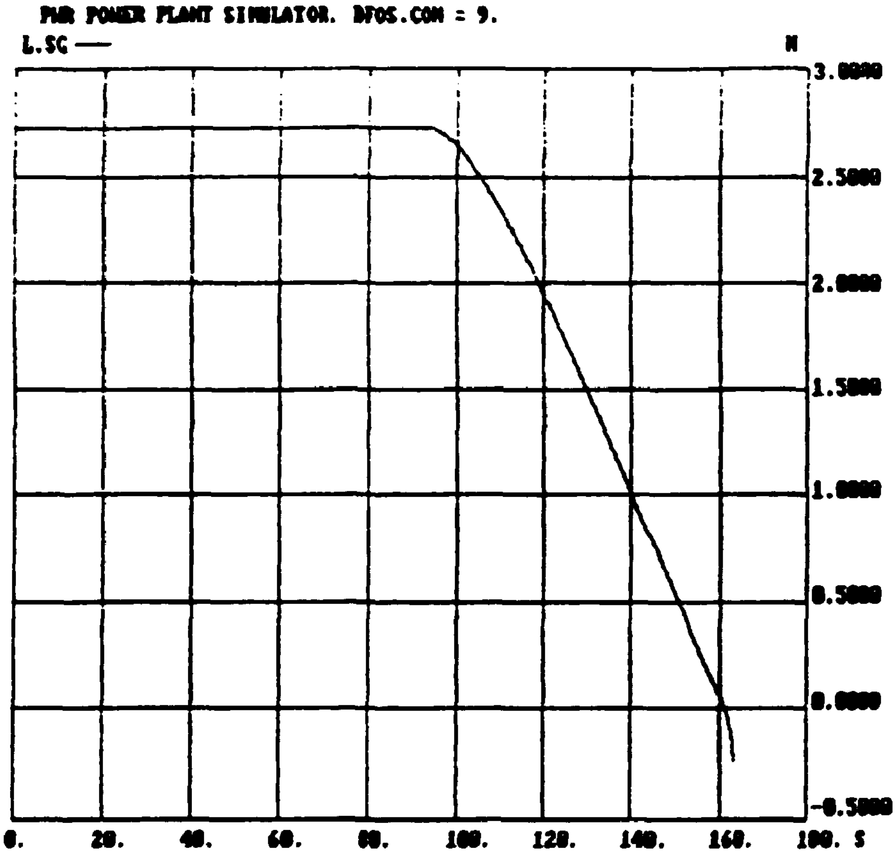
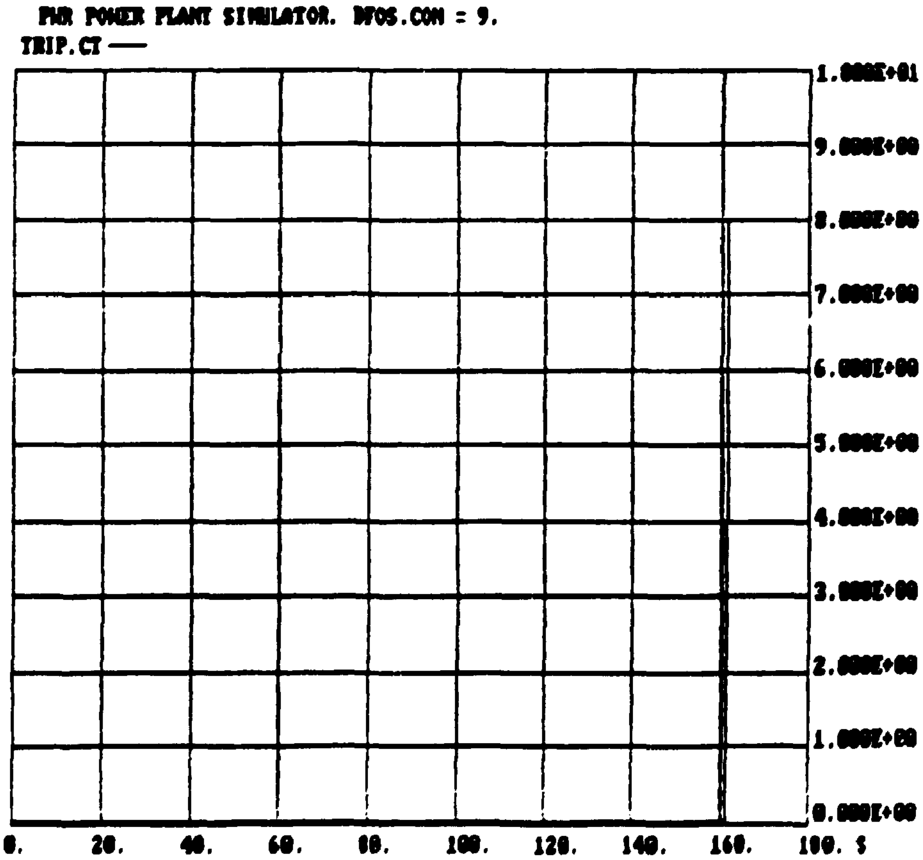


Fig.11.3. Steam generator level and trip signal.



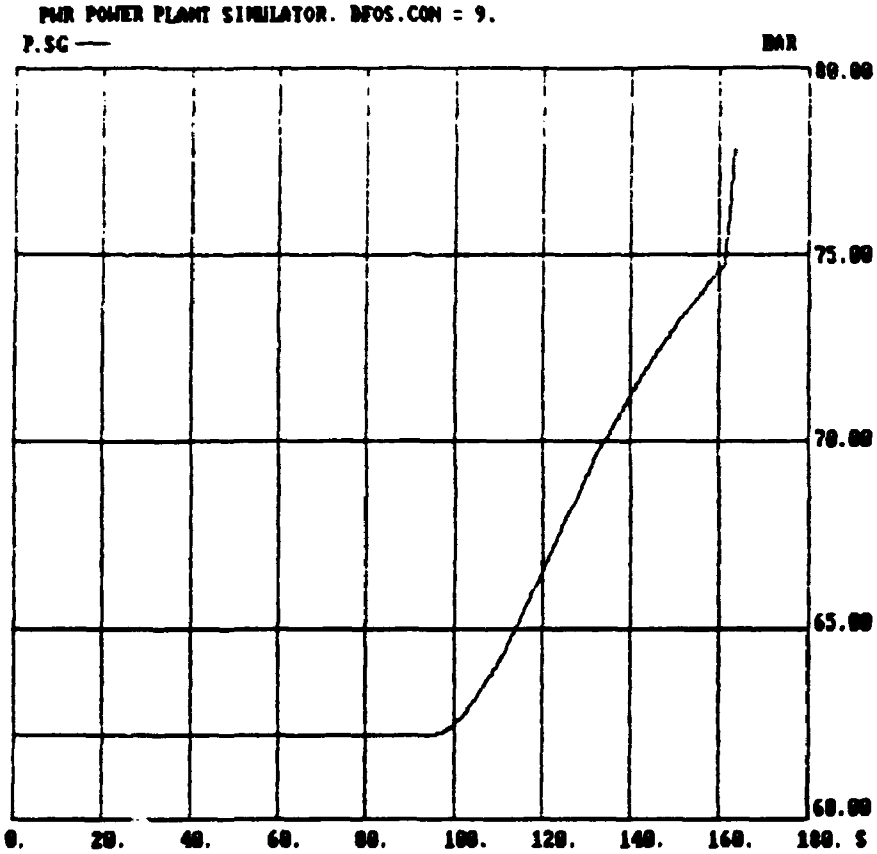
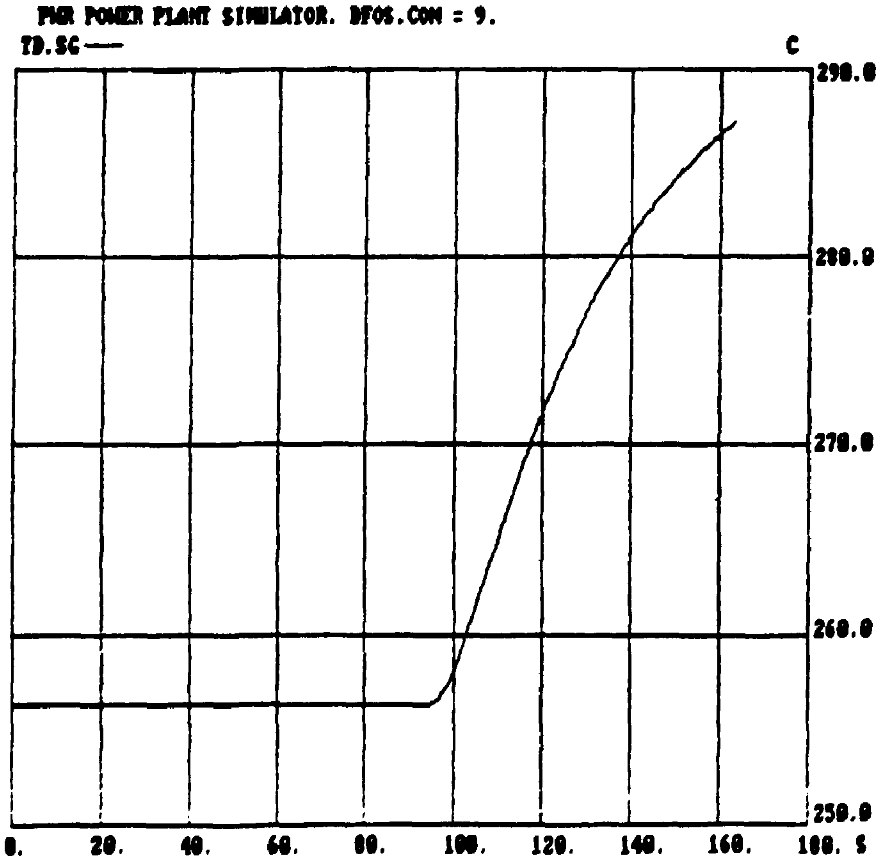


Fig.11.4. Steam generator pressure and down comer temperature.



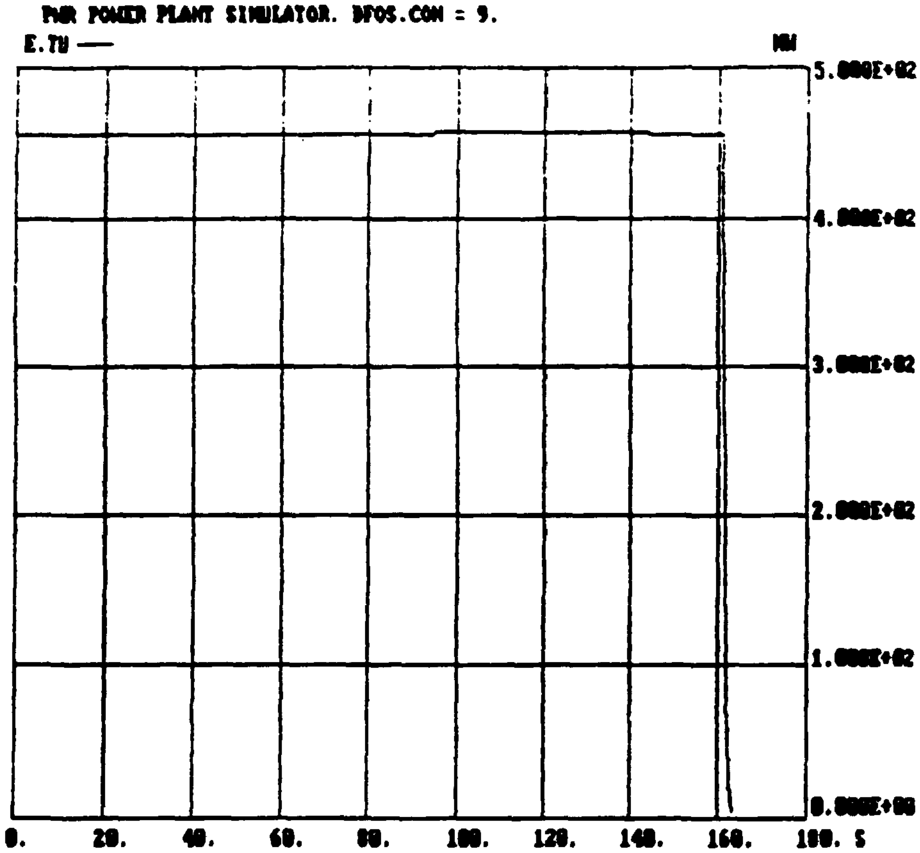
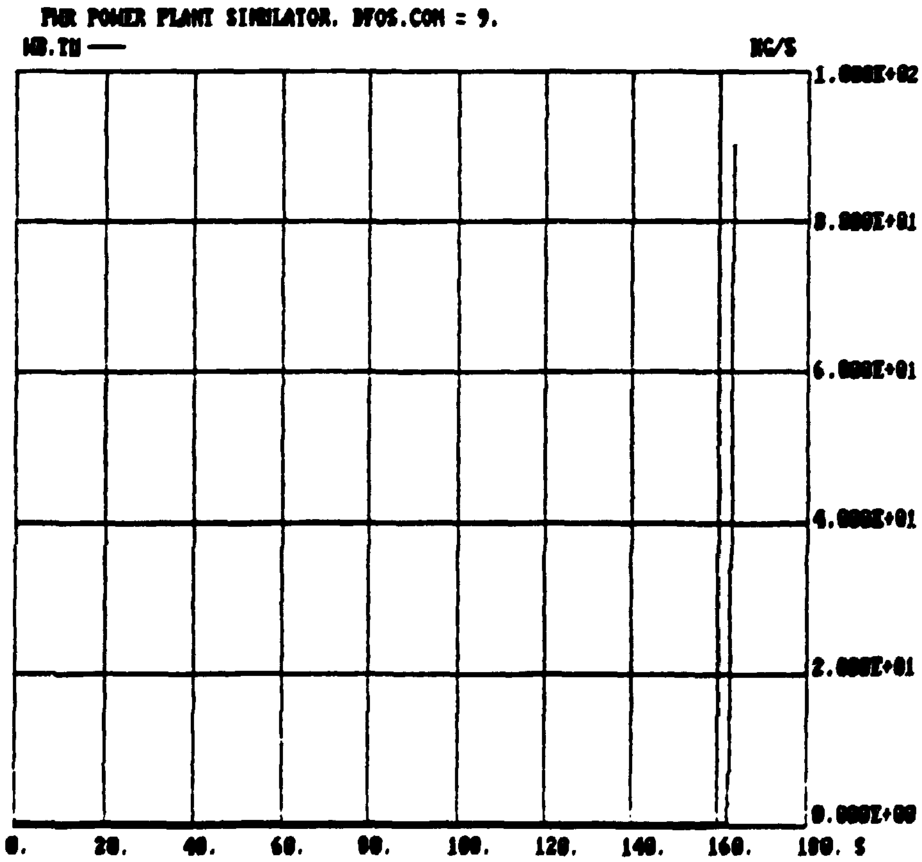


Fig. 11.5. Turbine power and
by-pass flow.



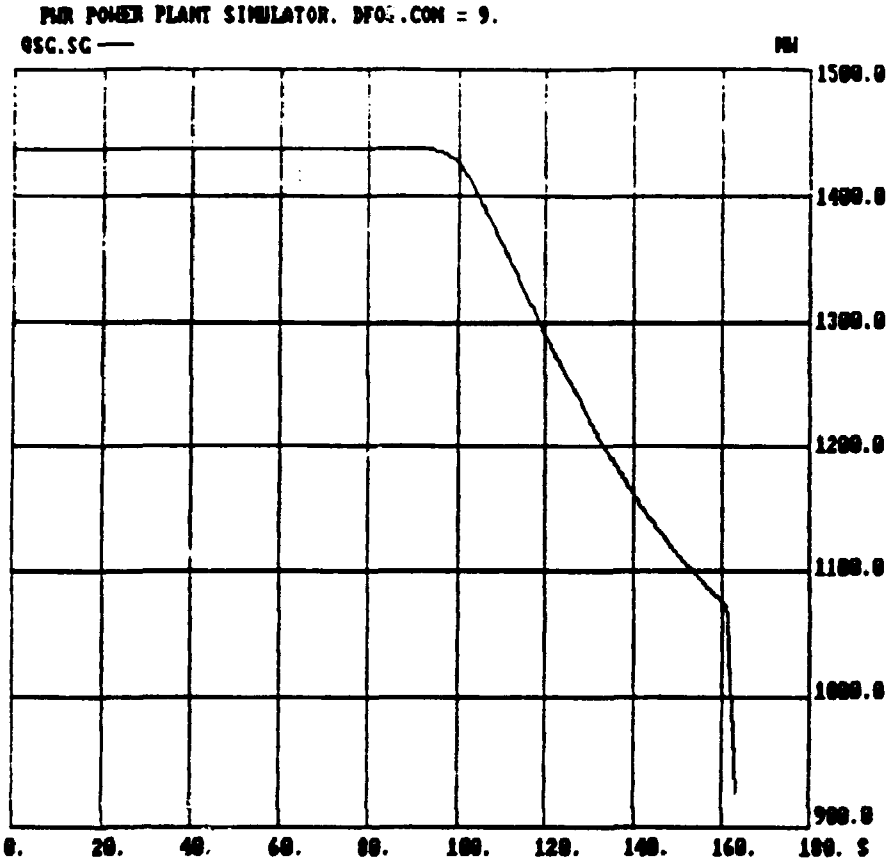
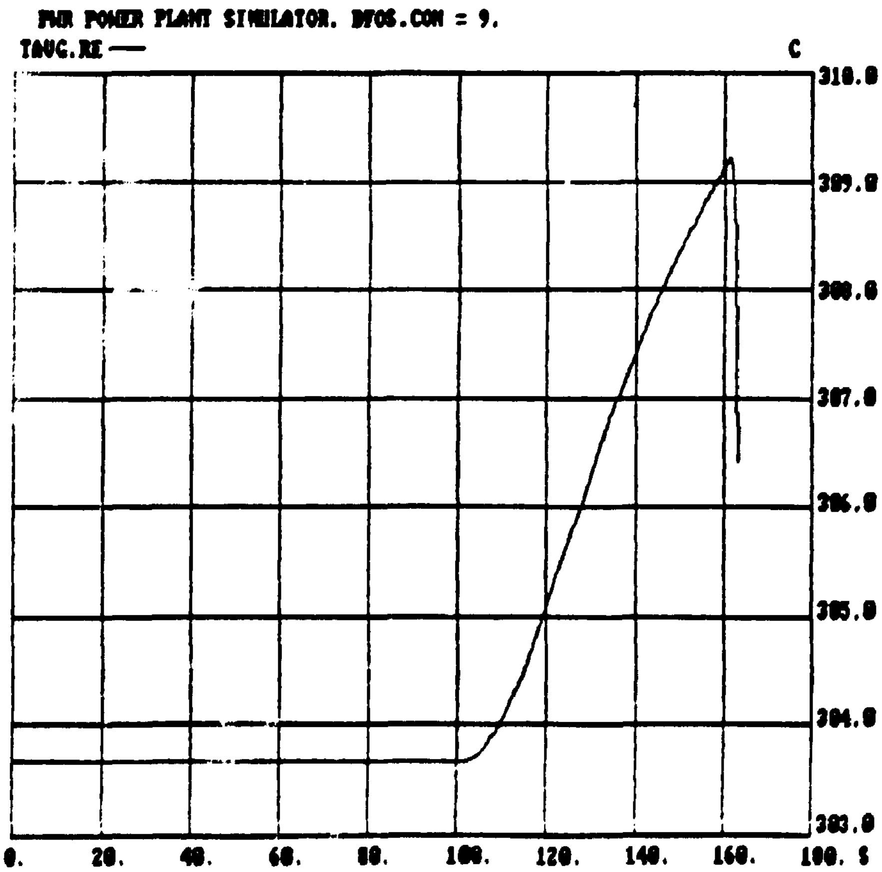


Fig.11.6. Steam generator heat transfer and reactor average temperature.



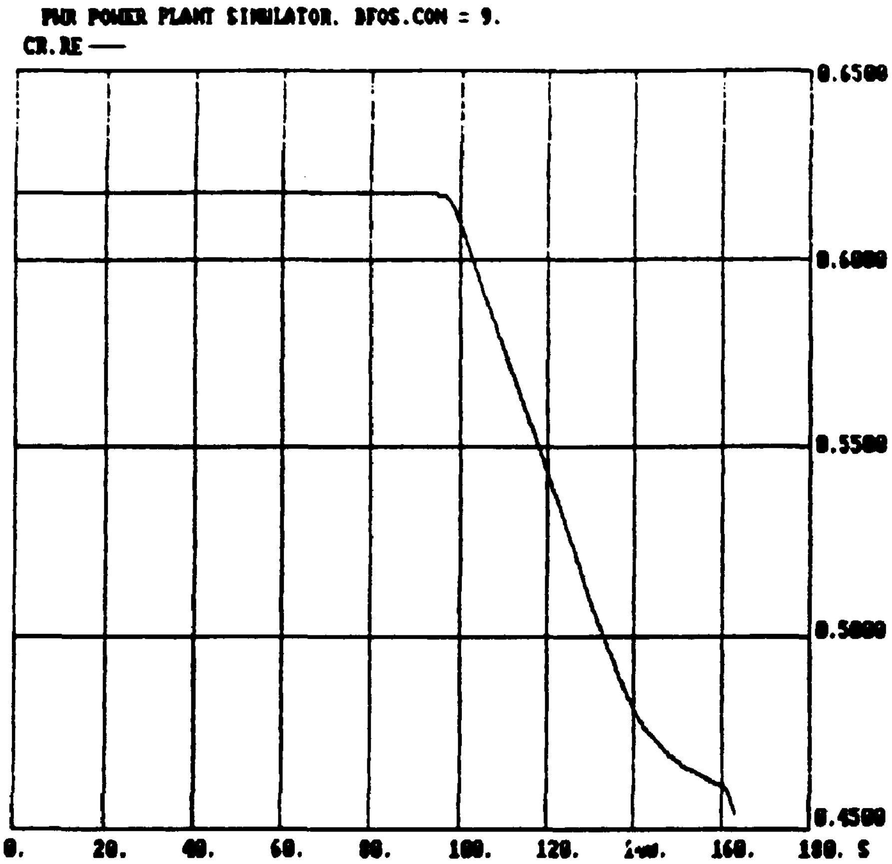
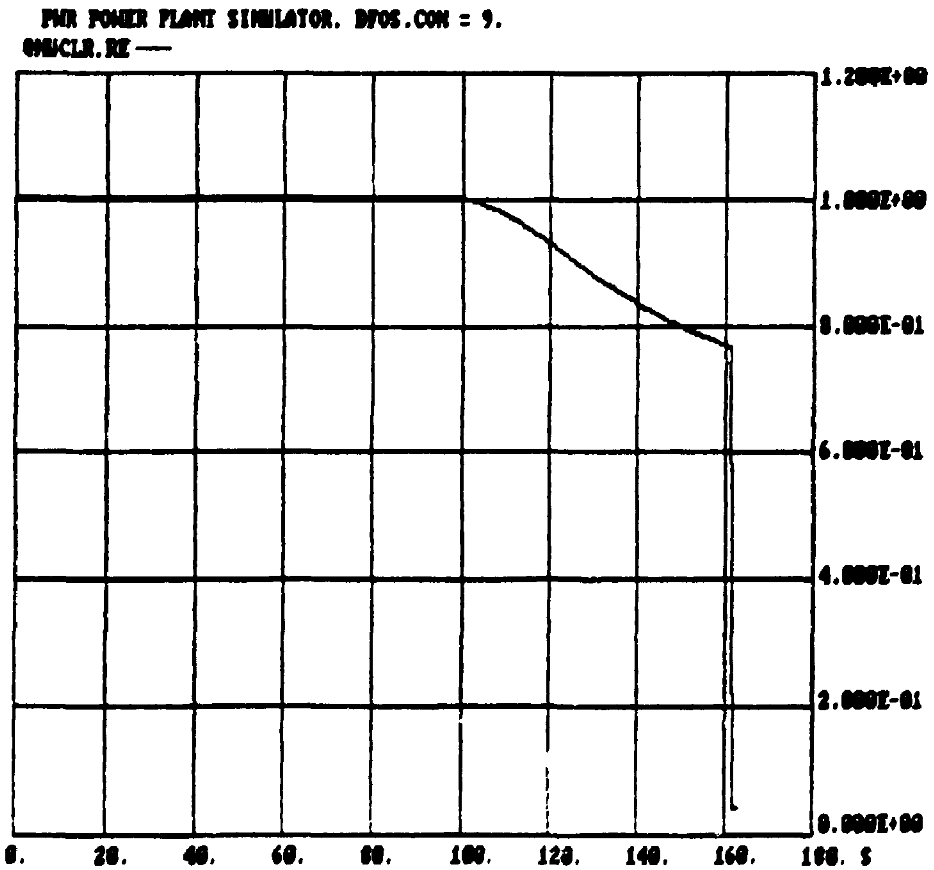


Fig.11.7. Control rod position and relative nuclear power.



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KOFOED, J.E. (1987). Ph.D. Thesis (to be published), Risø 1987.

NASH, G. (1980). An Appraisal of Subcooled Boiling and Slip Ratio from Measurements made in Lingen Boiling Water Reactor. Nuclear Technology, Vol. 51, Nov. 1980.

APPENDIX A1

Units used throughout the model:

pressure:	bar
energy	MJ
mass	kg
time	sec.
length	m
activity	Bq

notice that $0.1 \dfrac{\text{kg MJ}}{\text{m}^3\text{ kg bar}} = 1$

APPENDIX A2

Physical data used in reactor module:

Volumes (m^3):

$V_{inl} = 6.34$	$V_{lp} = 14.24$	$V_c = 14.138$
$V_{up} = 23.83$	$V_{hl} = 3.13$	$V_{ct} = 3.46$
$V_p = 4.40$	$V_{cl} = 3.41$	

W_{pnorm} = 4320 Kg/s

T_{unorm} = 652 ^oC $\quad$ T_{cnorm} = 303.3 ^oC

Q_{norm} = 2765 MW

C_{fuel} = 26.3376 MJ/^oC

$C_{TU} = -2.5\cdot10^{-5}$ $\quad$ $C_{TC} = -30.0\cdot10^{-5}$ $\quad$ $C_{CR} = 900\cdot10^{-5}$

$l = 10^{-3}s$ $\quad$ $\beta = 6648\cdot10^{-6}$

$\beta_1 = 992\cdot10^{-6}$ $\quad$ $\beta_2 = 3840\cdot10^{-6}$ $\quad$ $\beta_3 = 1616\cdot10^{-6}$

$\lambda_1 = 1.82\ s^{-1}$ $\quad$ $\lambda_2 = 0.249\ s^{-1}$ $\quad$ $\lambda_3 = 0.0288\ s^{-1}$

$H = 7.92945$ MW/^oC

REACTOR AND PRIMARY LOOP
========================

```
STATE VARIABLES:
TINL=     283.84   TLP=        283.84    TC=         322.76    TU=         653.76
TUP=      322.76
THL=      322.76   TCT=        283.84    TP=         283.84    TCL=        283.84
CR=       0.6174   QA1=        1.51E+03  QA2=        4.28E+04  QA3=        1.56E+05
MOR=      0.500

INPUT VARIABLES:
RODSPD=   2.86E-07 SRODM=      0.0       TRIP=       0.0       SSCRAM=     0.0
TSGO=     283.8    PP=         135.0
SPPP=     1.0      FOP=        1.0       SPLOP=      1.0       LLOP=       0.00E+00

ALGEBRAIC VARIABLES:
QNUCLR=   1.004    QRE=        1388.0    TAVG=       303.66
WRE=      6480.0   WPR=        1.0000
TEXP=     -0.41E-05 PEXP=      0.23E-01  SPM=        0.00
WOP=      1.00     POP=        1.00

RFLP=     758.3    RFC=        717.7     RFUP=       669.0     RFCT=       758.3
CP=       0.55E-02
QTRANS=   2776.1   QNULC=      2776.1
DRTU=     -4.39E-05 DRTC=      -1.08E-04 DRCR=       3.52E-04  KEFF=       1.000200
TTRIP=    -1.00E+00 QTRIP=     0.0       TPUMP=      -1.00E+00 WPRB=       0.00E+00
```

APPENDIX A3

Physical data used in the pressurizer module:

Volumes:

minimum water volume	V_{fmin}	= 1.77 m^3
water volume span	V_{span}	= 37.7643 m^3
total volume	V_{tot}	= 41.30 m^3

Safety valve:

opening pressure	172.4 bar
capacity	49.7 Kg/s

Volume control tank pump:

flow to speed ratio	7.0 Kg/s

Total mass capacity of volume control tank:

$m_{VCTF} = 3.141592 \cdot 10^4$ Kg

For further data cf. Fig. 3.2.

```
PRESSURIZER
===========

STATE VARIABLES:
P=          155.0    HG=        2.61E+00 HF=        1.63E+00 VF=          20.08
MVCTR=      0.49

INPUT VARIABLES AND PARAMETERS:
TI=        322.76    TL=        283.84   PEXP=      3.13E-02 TEXP=      -3.76E-06
ZP=       4.11E-01   ZV=        3.42E-01 WLD=       6.95E-03
LEAKG=    0.00E+00   LEAKW=     0.00E+00 LEAKPS=    0.00E+00
SPH=        0.000    SBH=       0.000
FVCP=       1.000
FR1=        0.00     FR2=       0.00     FSAF=      0.00     FSPR=        0.00
WLED=     2.80E+00

ALGABRAIC VARIABLES:
WLV=        0.48     WK=        4.60E-02 G=         1.91E-01
WI=      -4.26E-01   WC=        5.36E-02 WE=        1.41E-01 WCHA=      2.39E+00
WR1=      0.00E+00   WR2=       0.00E+00 WSV=       0.00E+00 WD=        2.80E+00


GP=       1.91E-01   GBAK=      0.00E+00 WR1=       0.00E+00 WR2=       0.00E+00
WIPLUS=   0.00E+00   WR=        0.00E+00
TSAT=      344.78    HGS=       2.61E+00 HFS=       1.63E+00 HFG=       9.70E-01
HI=       1.48E+00   HK=        1.25E+00
GASSAT=      T       WATSAT=       T     UPBACK=       F     UPRV1=        F
UPRV2=       F

CONTAINMENT ACTIVITY

====================

STATE VARIABLES:
ACN16=   0.000E+00

INPUT VARIABLES:
LEAKG=      0.000    LEAKW=       0.000
GNUCLR=     1.004
```

APPENDIX A5

Physical data used in the steam generator module:

Lengths (m):

$De_p = 1.688 \cdot 10^{-2}$	$De_s = 7.42 \cdot 10^{-2}$	$De_t = 3.161$
$De_r = 1.715$	$De_d = 0.8238$	
$l_c = 8.50$	$l_t = 1.14$	$l_r = 4.13$
$l_d = 9.64$	$dr = 1.09 \cdot 10^{-3}$	

Surfaces (m^2/m):

$O_p = 247.7$	$O_u = 269.7$	$O_s = 279.7$

Cross sections (m^2):

$A_p = 1.045$	$A_s = 5.190$	$A_t = 7.85$
$A_r = 2.31$	$A_b = 12.08$	$A_d = 0.533$

Volumes (m^3):

$V_p = 17.77$	$V_s = 44.12$	$V_t = 8.95$
$V_r = 9.54$	$V_{top} = 105.74$	$V_b = 31.74$
$V_{dc} = 5.14$	$V_{pi} = 4.5$	$V_{po} = 4.5$

Heat capacity of U-tube

$C_r = 8.79 \ MJ/^oC$

Thermal conductivity in U-tube:

$\lambda = 15.5 \cdot 10^{-6} \ MW/m^oC$

Single phase friction parameter:

$F_f = 4.22 \cdot 10^{-2}$

Friction pressure drop parameters

$K_{dps} = 12.0$	$K_{dpt} = 5.0$	$K_{dpr} = 200.0$
$K_{dpd} = 15.0$		

Pressure derivative time lag constant:

$\tau_P = 0.3$ sec.

Relation between relative void volume and outlet void fraction F_α:

$$F_\alpha\left(\frac{V_g}{V_S}\right) = 2.33-1.74\left(\frac{V_g}{V_S}\right)$$

Heat transfer parameter $H_P(T)\left(\frac{KJ\ Kg^{0.2}}{{}^oC\ Kg(m/s)^{0.2}}\right)$:

$$H_P(T) = 0.155828 \cdot 10^{-4}\ T^2 - 0.772876 \cdot 10^{-2}\ T + 1.82569$$

Slip correlation by Bankoff-Jones:

$$S(P_B,\alpha) = (1-\alpha)/(K_S-\alpha+(1-K_S)\alpha^R)$$

where

$$K_S = 0.09\ P + 0.712$$
$$R = (0.46\ P + 0.18)\ P + 3.33$$
$$P = P_B \cdot 14.50/1000$$

```
STEAM GENERATOR
===============

STATE VARIABLES:
TI1=       322. 8   TO1=         294. 3   TO2=         283. 8   TPO=         283. 8
TR1=       295. 0   TR2=         284. 9
TB=        256. 2   TD=          256. 2
P=          62. 2   DP=       -0. 85E-05  VCS-REL=   0. 47E+00  VCT-REL=    0. 71E+0C
VCR-REL= 0. 71E+00
VD=      6. 00E+00  L=         2. 73E+00

INPUT VARIABLES AND PARAMETERS:
PP=        155. 0   WP=           1. 00   WF=          438. 3   WL=          438. 3
TPI=       322. 8   TI=          188. 5   LS=        0. 00E+00  LP=        0. 00E+0C
KDPS=    1. 20E+01  KDPT=      5. 00E+00  KDPR=      2. 00E+02  KDPD=      1. 50E+01
TAUP=    2 00E-01

ALGEBRAIC VARIABLES:
QSG=     1436. 3    QEVAP=     1024. 3
TSAT=    277. 83
PEXP=    0. 83E-02  TEXP=      0. 35E-06
TRY1=    0. 28E+03  TRY2=      0. 28E+03


TM1=       315. 0   TM2=         291. 6   TSAT=        277. 8
B1=        0. 728   B2=          0. 741   SLIP-RISER=  2. 108
ALFAS=     0. 713   ALFAT=       0. 713   ALFAR=       0. 713
VFS-REL= 0. 53E+00  VFT-REL=   0. 29E+00  VFR-REL=   0. 29E+00  RFS=       7. 55E+02
WS=      2. 41E+03  WFS=       1. 97E+03  WGS=       4. 38E+02  WFT=       1. 97E+03
WGT=     4. 38E+02  WFR=       1. 97E+03  WGR=       4. 38E+02
KP1=     3. 60E+01  KP2=       3. 53E+01  KS1=       4. 21E+01  KS2=       3. 33E+01
LAMBDA=  1. 55E-05
HP1=     8. 03E+01  HP2=       7. 68E+01  HS1=       1. 19E+02  HS2=       6. 81E+01
QP1=     7. 22E+02  QP2=       2. 36E+02  QS1=       7. 22E+02  QS2=       2. 36E+02
QK=      6. 83E+02  QL=        0. 00E+00
DPS=     2. 73E+01  DPT=       7. 39E-03  DPR=       2. 57E+01  DPD=       2. 55E+01
FPDS=      0. 206   FPDT=        0. 000   FPDR=        0. 194   FPDD=        0. 192
```

APPENDIX A6

Physical data used in the turbine and condenser module:

Flow coefficients:

$K_e = 0.3306671 \cdot 10^{-5}$	$K_h = 13.0$
$K_{hl} = 1630$	$K_{vm} = 150$
$K_l = 121.35$	$K_{rv} = 1.0155$
$K_{sv} = 139$	$K_b = 11.86$

Volumes (m^3)

$V_{sl} = 214.2$	$V_h = 10.0$	$V_r = 240$
$V_t = 284$	$V_{mo} = 18.6$	$V_l = 156$

Heat transfer coefficents:

$K_{qt} = 4.54$	$K_{cw} = 55$	$C_{Kqr} = 294$

Heat capacities:

$C_{tr} = 5.315$ MJ/°C	$C_{cw} = 378$ MJ/°C
$C_{ct} = 41$ MJ/C	$C_{pc} = 4.2 \cdot 10^{-3}$ MJ/Kg °C

Condenser mass capacity:

$M_{ctot} = 2 \cdot 10^5$ Kg

Turbine extraction fractions:

$S_{plith} = 0.8$ $S_{plitl} = 0.95$

Turbine therminal efficiency:

$\gamma_{hp} = 0.781$ $\gamma_{lp} = 0.87867$

TURBINES AND CONDENSER

STATE VARIABLES:

PV=	60.75	PH=	46.31	PT=	3.70	PL=	3.45
PM=	60.38						
HHP=	655.7	HRTV=	1345.57	HRHV=	1223.45	HLP=	669.27
TTR=	256.88	TCON=	29.56	TCO=	18.76	MCONR=	0.46

INPUT VARIABLES AND PARAMETERS:

WV=	602.0	WPHH=	118.7	WPHL=	25.1	WCON=	393.3
WCW=	19000.0						
PE=	62.18	TCI=	8.00				
XRV=	0.00	XBPV=	0.00				
FSV=	0.0	FRV=	0.0	FBPV=	0.0	FHPV=	0.0
FRHV=	0.00	FLPV=	0.00				
XRHV=	1.000	XLPV=	1.000				
TRIP=	0.0						
GHP=	0.78	GLP=	0.88				

ALGABRAIC VARIABLES:

E=	456.0	WSL=	657.4	PC=	0.041		
PSH=	12.23	HSH=	2.90	WMS=	65.0	TMS=	140.82
WRH=	55.4	TRH=	275.93	PSL=	0.21	HSL=	2.34
WSV=	0.0	WH=	602.0	WL=	418.4	WB=	0.0
QCT=	859.0						
EH=	197.3	EL=	258.7				
WRV=	0.0						

WM=	55.4	WRV=	0.0	WSV=	0.0	WB=	0.0
WH=	602.0	WT=	483.4	WTI=	418.4	WRO=	418.4
WTO=	418.4	WL=	418.4	WLO=	393.3		
HV=	2.78	HHO=	2.43	HRO=	2.93		
HC=	2.31	DHH=	0.34	DHL=	0.62		
TMS=	140.82	TRM=	196.13	TRO=	233.13	TM=	275.93
EL=	258.7	EH=	197.3				
QRR=	86.5	QTR=	86.5	QCT=	859.0	QCV=	859.0
XHO=	0.86	XLO=	0.90				

APPENDIX A7

Physical data used in the feedwater line module

Pump characteristics:

$A_1 = -1.342057 \cdot 10^{-5}$	$A_2 = -5.242410 \cdot 10^{-5}$
$B_1 = 3.771918 \cdot 10^{-3}$	$B_2 = 2.357449 \cdot 10^{-2}$
$C_1 = 10$	$C_2 = 100$

Friction pressure drops (bar)

$\Delta P_{f1} = 5$	$\Delta P_{f2} = 5$

Feedwater tank volume 10 m^3

Preheater 1:

$C_t = 2.54$ MJ/°C	$C_f = 42.6$ MJ/°C
$K_{st} = 30.30$ MW/°C	$K_{tf} = 30.3$ MW/°C

Preheater 2:

$C_t = 2.54$ MJ/°C	$C_f = 22.8$ MJ/°C
$K_{st} = 29.20$ MW/°C	$K_{tf} = 29.2$ MW/°C

```
FEEDWATER LINE
==============

STATE VARIABLES:
TFW=      188.46   TFWT=        117.54   TC=          61.32
TT1=       59.60   TT2=         181.97
LFWT=      0.500   MOR=          0.500

INPUT VARIABLES:
SPFWP=     0.864   SPCP=         0.871
PC=         0.04   TCON=         29.56
PLP=        0.21   HLPV=          2.34
PHP=       12.23   HHP=           2.50
WMS=       64.97   TMS=         140.82
WRH=       55.39   TRH=         275.93
PSG=       62.18   LEAK=          0.00
FFWP=      1.000   FCP=          1.000
FOS=         1.0   SPLOS=          1.0   LLOS=          0.0

ALGABRAIC VARIABLES:
WFW=       657.4   WCON=         373.3   WLP=          25.1   WHP=          118.7
WOS=         1.0   POS=           1.00

PFWT=        1.8   TPH1=          61.3   TPH2=        188.9
SSM=         0.0
TPUMP=  -0.10E+01  WFOLD=          0.0
```

APPENDIX A8

Physical data used in the lubrication oil systems.

Pressure limits on by-pass valve:

P_{01} = 2 bar P_{02} = 2.5 bar

Constants:

K_1 = 1 K_2 = 1 K_3 = 0.5

Minimum oil flow:

W_{norm} = 0.5 Kg/s

Total oil mass:

M_{otot} = 50 Kg

APPENDIX A9

Data used in the controller and trip system module (cf. figures in section 9).

Primary pressure controller C_1:

$K_{11} = 0.66$ $\tau_{11} = 300$

Pressurizer water level controller C_2

$K_{21} = 1$ $\tau_{21} = 300$

Steam generator water level controller C_3:

$K_{31} = 2$ $\tau_{31} = 2$

$K_{32} = 1$ $\tau_{32} = 5$

$\tau_{33} = 150$

$\tau_{34} = 10$

Reactor power controller C_4:

$\tau_{41} = 40$ $\tau_{42} = 30$

$\tau_{43} = 8$ $\tau_{44} = 50$

$\tau_{45} = 10$

Turbine power controller C_5:

$K_{51} = 25$ $\tau_{51} = 5$

$\tau_{52} = 0.5$

$$F_V(x) = \begin{cases} 1.6365x & \text{for } x < 0.5 \\ -0.2458774 + 3.15446707x - 2.03126323x^2 & \text{for } x > 0.5 \end{cases}$$

By-pass valve controller C_6:

$K_{61} = 7.25 \cdot 10^{-2}$ $\tau_{61} = 300$

Secondary relief valve C_7:

$K_{71} = 0.2899$ $\tau_{71} = 240$

Feedwater tank level controller:

$K_{81} = 1$ $\tau_{81} = 150$

CONTROLLERS

```
INTEGRAL ERROR SIGNALS:
Z11=     -1.39E-02
Z21=      3.49E-01
Z31=      6.60E-01 Z32=      6.60E-01 Z33=      4.32E-01 Z34=      8.64E-01
Z41=     -3.49E-03 Z42=      3.03E+02 Z43=      3.03E+02 Z44=      3.03E+02
Z51=      1.88E-01 Z52=      4.70E+00 Z53=      5.14E-01
Z61=      0.00E+00
Z71=      0.00E+00
Z81=      8.71E-01

INPUT VARIABLES:
PP=       154.99   PPO=      155.10    WLV=      0.485    TAVG=     303.66
GNUCLR=   1.004    XTL=      2.73      WL=       657.4    WF=       657.4
THL=      322.76   TCL=      283.84    PHP=      46.31
E=      0.456E+03  EO=     0.456E+03
LFWT=   0.500E+00  LFWTO=  0.50E+00   PSL=      60.75
CL=     0.463E+00  PC=      0.0412     WPR=      1.00     SCRAM=    0.00
B1=       0.0      B2=      0.0        B3=       0.0      B4=       0.0
B5=       0.0      B6=      0.0        B7=       0.0      B8=       0.0

PARAMETERS:
K11=      6.67E-02 TAU11=    3.00E+02 K21=      1.00E+00 TAU21=    3.00E+02
K31=      2.00E+00 K32=      1.00E+00
TAU31=    2.00E+00 TAU32=    5.00E+00 TAU33=    1.50E+02 TAU34=    1.00E+01
TAU41=    4.00E+01 TAU42=    3.00E+01 TAU43=    8.00E+00 TAU44=    5.00E+01
TAU45=    1.00E+01
K51=      2.50E+01 TAU51=    5.00E+00 TAU52=    5.00E-01
K61=      7.25E-02 TAU61=    3.00E+02 K71=      2.90E-01 TAU71=    2.40E+02
K81=      1.00E+00 TAU81=   1.500E+02

ALGABRAIC VARIABLES:
Y11=      4.11E-01
Y21=      3.42E-01 Y22=      6.95E-03
Y31=      8.64E-01
Y41=      2.86E-07
Y51=      6.02E+02 Y52=      5.14E-01
Y61=      0.00E+00
Y71=      0.00E+00
Y81=      8.71E-01
TRIP=     0.00E+00 PLO=      4.78     SLO=      6.60

VALUES AT START OF CONTROLLER DRIFT:
TB1=     -1.000E+00   YB1=    0.000E+00
TB2=     -1.000E+00   YB2=    0.000E+00
TB3=     -1.000E+00   YB3=    0.000E+00
TB4=     -1.000E+00   YB4=    0.000E+00
TB5=     -1.000E+00   YB5=    0.000E+00
TB6=     -1.000E+00   YB6=    0.000E+00
TB7=     -1.000E+00   YB7=    0.000E+00
TB8=     -1.000E+00   YB8=    0.000E+00
```

APPENDIX B.

```
MODULE  CT
************************************************************
STATE VARIABLES        16
------------------------------------------------------------
NAME          SCT    DIMENSION    TEXT
------------------------------------------------------------
Z11           1                   INTEGRAL CONTROLLER SIGNALS
Z21           2
Z31           3
Z32           4
Z33           5
Z34           6
Z41           7
Z42           8
Z43           9
Z44           10
Z51           11
Z52           12
Z53           13
Z61           14
Z71           15
Z81           16

ALGEBRAIC VARIABLES  13
------------------------------------------------------------
NAME          ACT    DIMENSION    TEXT
------------------------------------------------------------
V11           1                   PRIMARY SIDE PRESSURE CONTROLLER OUTPUT
V21           2                   VOLUME CONTROL TANK PUMP CONTROL SIGNAL
V22           3                   BACKUP HEATER CONTROL SIGNAL
V31           4                   SEC. SIDE FEEDWATER PUMP CONTROL SIGNAL
V41           5      1/S          CONTROL ROD SPEED
V51           6      KG/S         STEAM FLOW TO HP-TURBINE VALVE
V52           7                   HP-TURBINE VALVE POSITION
V61           8                   BY-PASS VALVE POSITION
V71           9                   SECONDARY SIDE RELIEF VALVE POSITION
V81           10                  CONDESATE PUMP CONTROL SIGNAL
TRIP          11                  TURBINE AND REACTOR TRIP (0=NO TRIP)
PLO           12                  PRESSURIZER LEVEL SETPOINT
SLO           13                  STEAM GENERATOR LEVEL SETPOINT

INPUT VARIABLES        28
------------------------------------------------------------
NAME          XCT    DIMENSION    TEXT
------------------------------------------------------------
PP            1      BAR          PRIMARY PRESSURE FROM PRESSURIZER
PPO           2      BAR          PRIMARY SIDE PRESSURE SET POINT
WLV           3                   WATER LEVEL IN PRESSURIZER (RELATIVE)
TAVG          4      C            REACTOR AVERAGE TEMPERATURE
QNUCLR        5                   RELATIVE NUCLEAR REACTOR POWER
XLT           6      M            WATER LEVEL IN STEAM GENERATOR
WL            7      KG/S         STEAM LINE FLOW
WF            8      KG/S         FEEDWATER FLOW SECONDARY SIDE
THL           9      C            PRIMARY SIDE HOT LEG TEMPERATURE
TCL           10     C            PRIMARY SIDE COLD LEG TEMPERATURE
PHP           11     BAR          HP-TURBINE INLET PRESSURE
E             12     MW           TURBINE POWER


EO            13     MW           TURBINE POWER SET POINT
PSL           14     BAR          STEAM LINE PRESSURE
LFWT          15                  FEEDWATER TANK LEVEL
LFWTO         16                    -      -      -    SETPOINT
B1            17                  BLOCKING SIGNAL PRIMARY PRESSURE CONTROL
B2            18                    -       -     PRESS. WATER LEVEL CTR
B3            19                    -       -     STEAM GEN. WAT. LEV. CTR
B4            20                    -       -     ROD POS. CONTROL
B5            21                    -       -     TURBINE POWER CONTROL
B6            22                    -       -     BY-PASS VALVE CONTROL
B7            23                    -       -     SEC. RELIEF VALVE CTR
B8            24                    -       -     FW TANK LEVEL CTR.
CL            25                  RELATIVE CONDERSER WATER LEVEL
PC            26     BAR          CONDERSER PRESSURE
WPR           27                  RELATIVE PRIMARY SIDE FLOW
SCRAM         28                  MANUAL SCRAM SIGNAL (0=NO SCRAM, 1=SCRAM)

PARAMETERS             24
------------------------------------------------------------
NAME          PCT    DIMENSION    TEXT
------------------------------------------------------------
K11           1                   AMPLIFICATION AND TIME CONSTANTS
TAU11         2
K21           3
TAU21         4
K31           5
K32           6
TAU31         7
TAU32         8
TAU33         9
TAU34         10
TAU41         11
TAU42         12
TAU43         13
TAU44         14
TAU45         15
K51           16
TAU51         17
TAU52         18
K61           19
TAU61         20
K71           21
TAU71         22
K81           23
TAU81         24
```

```
MODULE: RE
----------------------------------------------------------------------
STATE VARIABLES        14
----------------------------------------------------------------------
NAME          SRE     DIMENSION    TEXT
----------------------------------------------------------------------
TINL          1       C            TEMPERATURE INLET CHAMBER
TLP           2       C            TEMPERATURE LOWER PLENUM
TC            3       C            TEMPERATURE OF WATER IN CORE REGION
TU            4       C            FUEL TEMPERATURE
TUP           5       C            TEMPERATURE UPPER PLENUM
THL           6       C            TEMPERATURE HOT LEG
TCT           7       C            TEMPERATURE CONNECTING TUPE
TP            8       C            TEMPERATURE PRIMARY PUMP CHAMBER
TCL           9       C            TEMPERATURE COLD LEG
CR            10                   CONTROL ROD POSITION (IN=0, OUT=1)
GAMMA(3)      11-13   MW
MOR           14                   RELATIVE MASS OF LUBRICATION OIL

ALGEBRAIC VARIABLES    9
----------------------------------------------------------------------
NAME          ARE     DIMENSION    TEXT
----------------------------------------------------------------------
QNUCLR        1                    RELATIVE NUCLEAR POWER
QRE           2       MW           NUCLEAR POWER
TAVG          3       C            REACTOR AVERAGE TEMPERATURE
WRE           4       KG/S         PRIMARY FLOW
WPR           5                    RELATIVE PRIMARY FLOW
PEXP          6                    PRESSURE COMPRESSIBILITY PRIMARY LOOP
TEXP          7                    TEMP.      -         -       -
WOP           8       KG/S         LUBRICATION OIL FLOW
POP           9       BAR          LUBRICATION OIL PRESSURE

INPUT VARIABLES        10
----------------------------------------------------------------------
NAME          XRE     DIMENSION    TEXT
----------------------------------------------------------------------
RODSPD        1       1/S          CONTROL ROD SPEED
SRODM         2                    CONTROL ROD MOTOR SWITCH (ON=0, OFF=1)
TRIP          3                    REACTOR TRIP INDICATOR (NO TRIP=0)
SSCRAM        4                    SCRAM MECHANISM SWITCH (WORKING=0,1=OFF)
TSGO          5       C            STEAM GENERATOR PRIMARY SIDE OUTLET TEMP
SPPP          6                    NORMALISED PRIMARY PUMP SPEED
FOP           7                    FRICTION FACTOR LUBRICATION OIL SYSTEM
SPLOP         8                    NORMALISED LUBRICATION OIL PUMP SPEED
LLOP          9       KG/S         LEAK OF LUBRICATION OIL FROM TANK
PP            10      BAR          PRIMARY PRESSURE

PARAMETERS             0
----------------------------------------------------------------------
```

```
MODULE: PR
----------------------------------------------------------------------
STATE VARIABLES        5
----------------------------------------------------------------------
NAME          SPR     DIMENSION    TEXT
----------------------------------------------------------------------
P             1       BAR          PRIMARY PRESSURE
HG            2       MJ/KG        ENTHALPY GAS PHASE
HF            3       MJ/KG        ENTHALPY WATER PHASE
VF            4       M**3         VOLUME OF WATER PHASE
MVCTR         5                    MASS (RELATIVE) OF WATER IN VOL. CTR. T.

ALGEBRAIC VARIABLES    11
----------------------------------------------------------------------
NAME          APR     DIMENSION    TEXT
----------------------------------------------------------------------
WLV           1                    RELATIVE WATER LEVEL
WK            2       KG/S         SPRAY COOLING RATE
Q             3       MW           HEATING POWER IN WATER PHASE
WCHA          4       KG/S         MASS FLOW FROM THE VOLUME CONTROL SYSTEM
WI            5       KG/S         MASS FLOW TO PRESSURIZER
WC            6       KG/S         CONDENSATION RATE IN STEAM PHASE
WE            7       KG/S         EVAPORATION RATE IN WATER PHASE
WR1           8       KG/S         FLOW RELIEF VALVE 1
WR2           9       KG/S           -      -      -   2
WSV           10      KG/S         FLOW SAFETY VALVE
WD            11      KG/S         FLOW TO VOLUME CONTROL TANK

INPUT VARIABLES        18
----------------------------------------------------------------------
NAME          XPR     DIMENSION    TEXT
----------------------------------------------------------------------
TI            1       C            TEMP. OF INLET FLOW FROM SURGE TUBE
TL            2       C            TEMP. OF SPRAY WATER
PEXP          3                    EXTERNAL PRESSURE COMPRESSIBILITY FAC
TEXP          4                    EXTERNAL TEMP. COMPRESSIBILITY FACTOR
ZP            5                    PRESSURE CONTROLLER SIGNAL
ZV            6                    WATER LEVEL CONTROLLER SIGNAL
WLD           7                    WATER LEVEL DEVIATION
LEAKG         8       KG/S         LEAK IN GAS PHASE
LEAKW         9       KG/S         LEAK IN WATER PHASE
LEAKPS        10      KG/S         LEAK PRIMARY TO SECONDARY SIDE
SPH           11                   SWITCH PROP. HEATER     (0=NORMAL,1=STOP)
SBH           12                     -      BACK UP HEATER (0=NORMAL,1=STOP)
FVCP          13                   VOLUME CONTROL PUMP FLOW FRACTION
FR1           14                   FUNCTION REL. VALVE 1 (0=NORMAL,1=STUCK)
FR2           15                   FUNCTION REL. VALVE 2 (0=NORMAL,1=STUCK)
FSAF          16                     -      SAFETY VALVE (0=NORMAL,1=LEAKS)
FSPR          17                     -      SPRAY VALVE  (0=NORMAL,1=STUCK)
WLED          18      KG/S         MASS FLOW INTO VOLUME CONTROL TANK

PARAMETERS             0
----------------------------------------------------------------------
```

```
MODULE  AC
================================================================
STATE VARIABLES        1
----------------------------------------------------------------
NAME          SAC     DIMENSION   TEXT
----------------------------------------------------------------
ACN16         1       BQ          ACTIVITY OF N-16 IN CONTAINMENT

ALGEBRAIC VARIABLES    0
----------------------------------------------------------------

INPUT VARIABLES        3
----------------------------------------------------------------
NAME          XAC     DIMENSION   TEXT
----------------------------------------------------------------
LEAKG         1       KG/S        LEAK OF GAS FROM PRESSURIZER
LEAKW         2       KG/S        LEAK OF WATER FROM PRESSURIZER
QNUCLR        3                   RELATIVE NUCLEAR POWER

PARAMETERS             0
----------------------------------------------------------------
```

```
MODULE: SC
================================================================
STATE VARIABLES       15
----------------------------------------------------------------
NAME          SSG     DIMENSION   TEXT
----------------------------------------------------------------
TI1           1       C           PRIMARY CORE INLET  TEMP. 1.ST SECTION
TO1           2       C           PRIMARY CORE OUTLET TEMP. 1.ST SECTION
TO2           3       C           PRIMARY CORE OUTLET TEMP. 2.ND SECTION
TPO           4       C           PRIMARY OUTLET TEMPERATURE
TR1           5       C           U-TUBE TEMPERATURE 1.ST SECTION
TR2           6       C           U-TUBE TEMPERATURE 2.ND SECTION
TB            7       C           TEMPERATURE MIXING CHAMBER
TD            8       C           TEMPERATURE DOWN COMER
P             9       BAR         PRESSURE
DP            10      BAR/S       PRESSURE DERIVATIVE AFTER TIME LAG
VGS           11      M**3        VOLUME OF STEAM PHASE, SECONDARY CORE
VGT           12      M**3        VOLUME OF STEAM PHASE, TOP CHAMBER
VGR           13      M**3        VOLUME OF STEAM PHASE, RISER
VD            14      M/S         SPEED OF WATER IN DOWN COMER
L             15      M           WATER LEVEL IN MIXING CHAMBER

ALGEBRAIC VARIABLES    7
----------------------------------------------------------------
NAME          ASG     DIMENSION   TEXT
----------------------------------------------------------------
QSG           1       MW          HEAT TRANSFERRED IN STEAM GEN.
QEVAP         2       MW          EVAPORATION HEAT FOR STEAM PRODUCTION
TSAT          3       C           STEAM TEMPERATURE
PEXP          4                   PRESSURE COMPRESSIBILITY, PRIMARY CORE
TEXP          5                   TEMP      -        ,      -      -
TRY1          6       C           OUTER U-TUPE SURFACE TEMPERATURE, 1.ST
TRY2          7       C             -     -      -          ,  -  , 2.ND

INPUT VARIABLES        8
----------------------------------------------------------------
NAME          XSG     DIMENSION   TEXT
----------------------------------------------------------------
PP            1       BAR         PRIMARY PRESSURE
WP            2                   RELATIVE PRIMARY CORE INLET MASS FLOW
WF            3       KG/S        FEEDWATER INLET MASS FLOW
WL            4       KG/S        STEAM LOAD
TPI           5       C           PRIMARY INLET TEMPERATURE
TI            6       C           FEEDWATER INLET TEMPERATURE
LS            7       KG/S        LEAK OF STEAM FROM STEAM GENERATOR
LP            8       KG/S        LEAK PRIMARY TO SECONDARY SIDE

PARAMETERS             5
----------------------------------------------------------------
NAME          PSG     DIMENSION   TEXT
----------------------------------------------------------------
KDPS          1                   SECONDARY SIDE FRICTION PARAMETER
KDPT          2                   TOP CHAMBER        -          -
KDPR          3                   RISER              -          -
KDPD          4                   DOWN COMER         -          -
TAUP          5       S           PRESSURE DERIVATIVE TIME LAG CONSTANT
```

MODULE TU

STATE VARIABLES 13

NAME	STU	DIMENSION	TEXT
PV	1	BAR	STEAM LINE PRESSURE
PH	2	BAR	HP-TURBINE INLET PRESSURE
PT	3	BAR	REHEATER PRESSURE, SEC. SIDE
PL	4	BAR	LP-TURBINE INLET PRESSURE
PM	5	BAR	REHEATER PRESSURE PRIM. SIDE
HHP	6	MJ	HP-TURBINE INLET TOTAL ENTHALPY
HRTV	7	MJ	REHEATER TOTAL ENTHALPY (LEFT)
HRHV	8	MJ	- - - (RIGHT)
HLP	9	MJ	LP-TURBINE INLET TOTAL ENTHALPY
TTR	10	C	REHEATER TUBE TEMPERATURE
TCON	11	C	CONDENSER TUBE TEMPERATURE
TCO	12	C	COOLANT OUTLET TEMPERATURE
MCONR	13		RELATIVE CONDENSER MASS

ALGEBRAIC VARIABLES 19

NAME	ATU	DIMENSION	TEXT
E	1	MW	TOTAL TURBINE POWER
WSL	2	KG/S	STEAM LINE FLOW
PC	3	BAR	CONDENSER PRESSURE
PSH	4	BAR	EXTRACTION PRESSURE HP-TURBINE
HSH	5	MJ/KG	- ENTHALPY -
WMS	6	KG/S	FLOW FROM MOISTURE SEPARATOR
TMS	7	C	TEMPERATURE OF MOISTURE FLOW
WRH	8	KG/S	FLOW FROM REHEATER
TRH	9	C	TEMPERATURE OF REHEATER FLOW
PSL	10	BAR	EXTRACTION PRESSURE LP-TURBINE
HSL	11	MJ/KG	- ENTHALPY -
WSV	12	KG/S	FLOW SAFETY VALVE
WH	13	KG/S	FLOW INTO HP-TURBINE
WL	14	KG/S	FLOW INTO LP-TURBINE
WB	15	KG/S	BY-PASS FLOW
QCT	16	MW	HEAT TRANSFER IN CONDENSER
EH	17	MW	HP-TURBINE POWER
EL	18	MW	LP-TURBINE POWER
WRV	19	KG/S	SECONDARY SIDE RELIEF VALVE FLOW

INPUT VARIABLES 19

NAME	XTU	DIMENSION	TEXT
WHPV	1	KG/S	FLOW THROUGH HP-TURBINE VALVE
WPHH	2	-	EXTRACTION FLOW HP-TURBINE
WPHL	3	-	- - LP-TURBINE
WCON	4	-	FEEDWATER FLOW FROM CONDENSER
WCW	5	-	COOLANT FLOW TO CONDENSER
PE	6	BAR	STEAM GENERATOR PRESSURE
TCI	7	C	COOLANT INLET TEMPERATURE
XRV	8		RELIEF VALVE POSITION
XBPV	9		BY-PASS VALVE POSITION
FSV	10		FUNCTION SAFETY VALVE (0=NORMAL, 1=LEAKS)
FRV	11		- RELIEF VALVE (0=NORMAL, 1=STUCK)
FBPV	12		- BYPASS VALVE (0=NORMAL, 1=STUCK)
FHPV	13		- HP-TUR. VALVE (0=NORMAL, 1=STUCK)
FRHV	14		- REHEAT. VALVE (0=NORMAL, 1=STUCK)
FLPV	15		- LP-TUR. VALVE (0=NORMAL, 1=STUCK)
XRHV	16		REHEATER VALVE POSITION
XLPV	17		LP-TURBINE VALVE POSITION
LC	18	KG/S	LEAK OF COOLANT INTO CONDENSER
TRIP	19		TURBINE TRIP SIGNAL

PARAMETERS 4

NAME	PTU	DIMENSION	TEXT
QHP	1		HP-TURBINE THERMAL EFFICIENCY
QLP	2		LP-TURBINE - -
SPLITH	3		HP-TURBINE EXTRACTION FACTOR
SPLITL	4		LP-TURBINE - -

```
MODULE: FW
==================================================================
STATE VARIABLES         7
------------------------------------------------------------------
NAME           SFW     DIMENSION    TEXT
------------------------------------------------------------------
TFW            1       C            TEMPERATURE FEEDWATER
LFWT           2                    RELATIVE FEEDWATER TANK LEVEL
TFWT           3       C            TEMPERATURE WATER IN FEEDWATER TANK
TC             4       C            CONDENSATE INLET TEMPERATURE TO FW.T.
TT1            5       C            TUBE TEMPERATURE PREHEATER 1
TT2            6       C              -       -          -     2
MOR            7                    RELATIVE MASS OF LUBRICATION OIL

ALGEBRAIC VARIABLES     6
------------------------------------------------------------------
NAME           AFW     DIMENSION    TEXT
------------------------------------------------------------------
WFW            1       KG/S         FEEDWATER FLOW
WCON           2       KG/S         FLOW OUT OF CONDENSER
WLP            3       KG/S         EXTRACTION FLOW LP-TURBINE
WHP            4       KG/S             -       -   HP-   -
WOS            5       KG/S         LUBRICATION OIL MASS FLOW
POS            6       BAR              -        -  PRESSURE

INPUT VARIABLES         22
------------------------------------------------------------------
NAME           XFW     DIMENSION    TEXT
------------------------------------------------------------------
SPFWP          1                    SPEED FEEDWATER PUMP
SPCP           2                      -   CONDENSATE PUMP
PC             3       BAR          CONDENSER PRESSURE
TCON           4       C                -    WATER TEMPERATURE
PLP            5       BAR          EXTRACTION PRESSURE LP-TURBINE
HLP            6       MJ/KG            -      ENTHALPY    -
PHP            7       BAR              -      PRESSURE HP-TURBINE
HHP            8       MJ/KG            -      ENTHALPY    -
WMS            9       KG/S         FLOW FROM MOISTURE SEPARATOR
TMS            10      C            TEMPERATURE MOISTURE SEP. FLOW
WRH            11      KG/S         FLOW FROM REHEATER
TRH            12      C            TEMPERATURE REHEATER FLOW
PSG            13      BAR          STEAM GENERATOR PRESSURE
LEAK           14      KG/S         WATER LEAK FROM FEEDWATER TANK
FFWP           15                   FEEDWATER PUMP FLOW FRACTION
FCP            16                   CONDENSATE PUMP FLOW FRACTION
FFWV           17                   FAILURE FEEDWATER VALVE
FCV            18                   FAILURE CONDENSATE VALVE
FOS            19                   LUBRICATION OIL FRICTION FACTOR
SPLOS          20                   SPEED LUBRICATION OIL PUMP
LLOS           21      KG/S         LEAK OF LUBRICATION OIL
MCONR          22                   RELATIVE MASS WATER IN OF CONDENSER

PARAMETERS              0
------------------------------------------------------------------
```

MODULE: CON CONNECTING SYSTEM

STATE VARIABLES 0

ALGEBRAIC VARIABLES 7

NAME	ACON	DIMENSION	TEXT
PPRPM	1	(NORM.)	PRIMARY PUMP SPEED
PPSET	2	BAR	PRESSURIZER LEVEL SETPOINT
ESET	3	MW	TURBINE POWER SETPOINT
LFWSET	4		FEEDWATER TANK LEVEL SETPOINT
FP	5		PRIMARY LUBRICATION OIL FRICTION
FS	6		SECOND. - - -
CWPR	7		COOLING WATER PUMP SPEED

INPUT VARIABLES 0

PARAMETERS 59

NAME	PCON	DIMENSION	TEXT
T1	1	S	RAMP DISTRUBANCE START TIME
T2	2	S	RAMP DISTURBANCE STOP TIME
PP	3	BAR	PRIMARY PRESSURE SETPOINT
DPP	4	BAR	PRIMARY PRESSURE SETPOINT DEVIATION
E	5	MW	TURBINE POWER SETPOINT
DE	6	MW	TURBINE POWER SETPOINT DEVIATION
LFWT	7		FEEDWATER TANK LEVEL SETPOINT
DLFWT	8		FEEDWATER TANK LEVEL SETPOINT DEV.
TCI	9	C	COOLANT INLET TEMPERATURE
DTCI	10	C	COOLANT INLET TEMPERATURE DEVIATION
FOP	11	NORM.	FRICTION PRIM. SIDE LUB. OIL SYSTEM
DFOP	12	-	FRICTION PRIM. SIDE LUB. OIL SYSTEM DEV
FOS	13	-	FRICTION SEC. SIDE LUB. OIL SYSTEM
DFOS	14	-	FRICTION SEC. SIDE LUB. OIL SYSTEM DEV
SPPP	15	NORM. SPEED	PRIMARY SIDE PUMP
DSPPP	16	-	PRIMARY SIDE PUMP DEVIATION
SPCWP	17	-	SEA WATER COOLANT PUMP
DSPCWP	18	-	SEA WATER COOLANT PUMP DEVIATION
B1	19	(BLOCK)	PRIMARY PRESSURE CONTROL (0=NORMAL)
B2	20	-	PRESSURIZER LEVEL CONTROL -
B3	21	-	STEAM GEN. LEVEL CONTROL -
B4	22	-	REACTOR POWER CONTROL -
B5	23	-	TURBINE POWER CONTROL -
B6	24	-	BY-PASS VALVE CONTROL -
B7	25	-	SEC. SIDE RELIEF VALVE CTR. -
B8	26	-	FEEDWATER LEVEL CONTROL -
FPSV	27	(FUNCTION)	PRIM. SAFETY VALVE (0=NORMAL, 1=LEAKS)
FPRV1	28	-	PRIM. RELIEF VALVE 1 (0=NORM, 1=STUCK)
FPRV2	29	-	PRIM. RELIEF VALVE 2 -
FSPRV	30	-	SPRAY VALVE -
FSSV	31	-	SEC. SAFETY VALVE (0=NORMAL, 1=LEAKS)
FSRV	32	-	SEC. RELIEF VALVE (0=NORM, 1=STUCK)
FBPV	33	-	BY-PASS VALVE -
FHPV	34	-	HP-TURBINE VALVE -
FLPV	35	-	LP-TURBINE VALVE -
FRHV	36	-	REHEATER VALVE -
FFWV	37	-	FEEDVATER VALVE (0=NORMAL, 1=CLOSED)
FCV	38	-	CONDENSATE VALVE -
XRHV	39	(NORM.)	REHEATER VALVE POSITION
XLPV	40	-	LP-TURBINE VALVE POSITION
WLED	41	KG/S	FLOW INTO VOLUME CONTROL TANK
LPG	42	KG/S	LEAK PRIMARY SIDE GAS PHASE
LPW	43	-	LEAK PRIMARY SIDE WATER PHASE
LSG	44	-	LEAK SECONDARY SIDE GAS PHASE
LSW	45	-	LEAK SECONDARY SIDE WATER PHASE
LPS	46	-	LEAK PRIMARY TO SECONDARY SIDE
LC	47	-	LEAK OF COOLANT INTO CONDENSER
LLOP	48	-	LEAK OF LUB. OIL PRIM. SIDE
LLOS	49	-	LEAK OF LUB. OIL SEC. SIDE
FFWP	50	(NORM.)	FEEDWATER PUMP FLOW FRACTION
FCP	51	-	CONDENSATE PUMP FLOW FRACTION
FVCP	52	-	VOLUME CONTROL PUMP FLOW FRACTION
SPLOP	53	NORM. SPEED	PRIMARY SIDE LUB. OIL PUMP
SPLOS	54	-	SEC. SIDE LUB. OIL PUMP
SRODM	55	SWITCH	CONTROL ROD MOTOR (0=NO FAILURE)
SCRM	56	-	SCRAM ROD MECHANISM -
SPH	57	-	PROPORTIONAL PRESS. HEATER -
SBH	58	-	BACK-UP PRESSURIZER HEATER -
MSCRM	59		MANUAL SCRAM SIGNAL (0= NO SCRAM)

APPENDIX C.

```
&             INPUT FILE FOR THE PWR POWER PLANT SIMULATOR
*SYST
PSYC                        S
CT         RE               PR          AC          SG          TU
FW         CON
&
&_______________________________________________________________________
&
&                          USER SPECIFIED INPUT DATA:
&                          ==========================
*DATA
&
& RAMP FUNCTION START AND STOP TIME:
& --------------------------------
 T1.CON        10.000      T2.CON            20.
&
&                                 DISTURBANCES:
&                                 -------------
&
& SETPOINTS PRIMARY PRESSURE, TURBINE POWER AND FEEDWATER TANK LEVEL
& ------------------------------------------------------------------
 PP.CON        155.10      DPP.CON           0
 E.CON         456.0       DE.CON            0
 LFWT.CON        0.5       DLFWT.CON         0
&
& COOLANT INLET TEMPERATURE:
& -------------------------
 TCI.CON       8.0000      DTCI.CON          0
&
& LUBRICATION OIL FRICTION, PRIMARY AND SECONDARY:
& -----------------------------------------------
 FOP.CON            1      DFOP.CON          0
 FOS.CON            1      DFOS.CON          0
&
& PRIMARY PUMP AND COOLING WATER PUMP SPEED:
& -----------------------------------------
 SPPP.CON           1      DSPPP.CON         0
 SPCWP.CON          1      DSPCWP.CON        0
&
&                                 FAILURES:
&                                 ---------
&
& CONTROLLER BLOCK SIGNALS  (0=NORMAL, +-1=DRIFT, 2=BLOCK):
& -------------------------------------------------------
 B1.CON             0      B2.CON            0      B3.CON            0
 B4.CON             0      B5.CON            0      B6.CON            0
 B7.CON             0      B8.CON
&
& VALVE FUNCTIONS (0=NORMAL):
& --------------------------
& Primary side
 FPSV.CON           0      FPRV1.CON         0      FPRV2.CON         0
 FSPRV.CON          0
&
& Secondary side
 FSSV.CON           0      FSRV.CON          0      FBPV.CON          0
 FHPV.CON           0      FLPV.CON          0      FRHV.CON          0

 FFWV.CON           0      FCV.CON           0
&
& VALVE POSITIONS, REHEATER - AND LP-TURBINE VALVE  <0-1>,(NORMAL=1):
& -----------------------------------------------------------------
 XRHV.CON           1      XLPV.CON          1
&
& VOLUME CONTROL TANK INLET FLOW (KG/S, NORMAL = 2.8 KG/S):
& --------------------------------------------------------
 WLED.CON         2.8
&
& LEAKS (KG/S, NORMAL = 0):
& ------------------------
& Primary side
 LPG.CON            0      LPW.CON           0
&
& Secondary side
 LSG.CON            0      LSW.CON           0
 LPS.CON            0      LC.CON            0
&
& Lubrication oil systems
 LLOP.CON           0      LLOS.CON          0
&
& PUMP FLOW FRACTIONS <0-1>, (NORMAL = 1):
& ---------------------------------------
 FFWP.CON           1      FCP.CON           1      FVCP.CON          1
&
& PUMP SPEEDS (NORMAL=1):
& ----------------------
& Lubrication oil systems
 SPLOP.CON          1      SPLOS.CON         1
&
& SWITCHES (0=NORMAL):
& -------------------
 SRODM.CON          0      SCRM.CON          0
 SPH.CON            0      SSH.CON           0
&
& MANUAL SCRAM (0=NO SCRAM):
& -------------------------
 MSCRM.CON          0
&
&
&
&                       END OF USERSPECIFIED INPUT FIELD.
&
&_______________________________________________________________________
&
K11.CT     =0.66667E-01 TAU11.CT   = 300.00     K21.CT     = 1.0000
TAU21.CT   = 300.00     K31.CT     = 2.0000     K32.CT     = 1.0000E+00
TAU31.CT   = 2.0000     TAU32.CT   = 5.0000     TAU33.CT   = 150.00
TAU34.CT   = 10.000     TAU41.CT   = 40.000     TAU42.CT   = 30.000
TAU43.CT   = 8.0000     TAU44.CT   = 50.000     TAU45.CT   = 10.000
K51.CT     = 25.000     TAU51.CT   = 5.0000     TAU52.CT   = .80000
K61.CT     =0.72000E-01 TAU61.CT   = 300.00     K71.CT     = .80000
TAU71.CT   = 240.00     K81.CT     = 1.0000     TAU81.CT   = 150.00
KDPS.SG    = 12.00      KDPT.SG    = 3.00       KDPR.SG    = 200.00
KDPD.SG    = 15.0000    TAUP.SG    = 0.2
SHP.TU     = 0.78100    SLP.TU     = 0.87867    SPLITH.TU  = 0.8
SPLITL.TU  =0.75
DATA.END
&
```

```
&                            USER SPECIFIED OUTPUT VARIABLES:
&                            ================================
*PRNT
& INT-1      PTIME-1     INT-2       PTIME-2     INT-3
  1.000       10.000      0.500       200.00      5.000       1
QNUCLR.RE    TAVG.RE     P.PR        P.SG        E.TU        L.SG
TRIP.CT      Y11.CT      Y21.CT      Y31.CT      Y41.CT      Y51.CT
TLP.RE       TC.RE       TU.RE       TUP.RE      WPR.RE      MDR.RE
WOP.RE       POP.RE      CR.RE
VF.PR        MVCTR.PR    WCHA.PR
ACN16.AC
TD1.SG       TD2.SG      TD.SG       VGS.SG      VGR.SG      QSG.SG
TRY1.SG      TRY2.SG     VD.SG
PV.TU        PH.TU       PT.TU       PL.TU       TCO.TU      SCT.TU
MCONR.TU     WBL.TU      PC.TU       WH.TU       WB.TU       TCON.TU
TFW.FW       LFWT.FW     TFWT.FW     MDR.FW      WFW.FW      WCON.FW
WDS.FW       POS.FW
PRNT.END
&
*PLOT
&
& NAME OF PLOTFILE:
& ----------------
 F2
&
*INPT
&
& HEADER FOR GRAPHS AND TABLES:
& ----------------------------
PWR POWER PLANT SIMULATOR.
&
&                      END OF USERSPECIFIED OUTPUT FIELD.
&
*CRCK_______________________________________________________________________
&                                                      SERVER
 0.001          0.06           0.09           1.0000E-03  10          RUNGE
&___________________________________________________________________________
&
*INCO
CT             16             13
-1.12717E-02 3.49194E-01 6.60000E-01 6.60000E-01 4.31891E-01 8.63782E-01
-3.47613E-03 3.03300E+02 3.03300E+02 3.03300E+02 1.88087E-01 4.70217E+00
 5.13519E-01 0.00000E+00 0.00000E+00 8.70571E-01
 4.11097E-01 3.42116E-01 7.07859E-03 8.63782E-01-7.29072E-11 6.02031E+02
 5.13519E-01 0.00000E+00 0.00000E+00 8.70571E-01 0.00000E+00 4.78000E-01
 6.60000E-01
RE             14             9
 2.83838E+02 2.83838E+02 3.22762E+02 6.53756E+02 3.22762E+02 3.22762E+02
 2.83838E+02 2.83838E+02 2.83838E+02 6.17370E-01 1.51341E+03 4.28202E+04
 1.53799E+05 5.00000E-01
 1.00369E+00 1.38803E+03 3.03661E+02 6.48000E+03 1.00000E+00 2.31343E-02
-1.56766E-07 1.00000E+00 1.00000E+00
PR             5              11
 1.54978E+02 2.60552E+00 1.63082E+00 2.00886E+01 4.72774E-01
 4.85077E-01 4.60000E-02 1.91621E-01 2.29481E+00-4.23807E-01 5.34439E-02
 1.40715E-01 0.00000E+00 0.00000E+00 0.00000E+00 2.80000E+00
AC             1              0


 0.00000E+00
SG             15             7
 3.22762E+02 2.94307E+02 2.83838E+02 2.83838E+02 2.94963E+02 2.84910E+02
 2.56241E+02 2.56241E+02 6.81764E+01 9.36658E-09 2.08614E+01 6.37858E+00
 6.79904E+00 5.79664E+00 2.72780E+00
 1.43633E+03 1.02434E+03 2.77830E+02 8.32443E-03-8.41348E-09 2.83892E+02
 2.81293E+02
TU             13             19
 6.07473E+01 4.62101E+01 3.70463E+00 3.44773E+00 6.03780E+01 6.39667E+02
 1.34557E+03 1.22344E+03 6.69273E+02 2.96863E+02 2.98897E+01 1.87638E+01
 4.62942E-01
 4.56000E+02 6.37426E+02 4.11704E-02 1.22297E+01 2.50721E+00 6.49740E+01
 1.40817E+02 5.92749E+01 2.79726E+02 2.11308E-01 2.38854E+00 0.00000E+00
 6.02031E+02 4.18406E+02 0.00000E+00 8.58750E+02 1.97279E+02 2.98721E+02
 0.00000E+00
FW             7              6
 1.88438E+02 5.00000E-01 1.17938E+02 6.13172E+01 8.99783E+01 1.81969E+02
 5.00000E-01
 6.57426E+02 3.93348E+02 2.80617E+01 1.18651E+02 1.00000E+00 1.00000E+00
CON            0              7
 1.00000E+00 1.55100E+02 4.56000E+02 5.00000E-01 1.00000E+00 1.00000E+00
 1.00000E+00
*REFV
ACN16.AC     ACN16.AC       1.000000E+9
DP.SG        DP.SG          1.000000E+00
REFV.END
*ENDE
```

APPENDIX D

Mean tempearture of water or steam flowing through a tube, exchanging heat with the tube wall:

Assume heat flows from the stream to an isotermal tube wall with tempearture T_r (cf. Fig. D). Energy balance for the volume element of length dx with temperature T(x) gives

$$Wc_p dT = K(T(x)-T_r)dx \tag{D1}$$

where W is water or steam flow, c_p is specific heat capacity of the flow and K is the heat transmission coefficient per unit length. Integrating D1 gives

$$\int_{T_i}^{T(x)} \frac{dT}{T(x)-T_r} = \frac{K}{Wc_p} \int_0^x dx \tag{D2}$$

which gives

$$T(x) = T_r + (T_i-T_r)\exp(\frac{K}{Wc_p} x) \tag{D3}$$

where T_i is the inlet temperature.

The mean flow temperature T_m is given by

$$T_m = \frac{1}{L} \int_0^L T(x)dx = T_r + \frac{(T_i-T_r)Wc_p}{KL} (\exp(\frac{K}{Wc_p}L)-1) \tag{D4}$$

and the outlet temperature T_o as

$$T_o = T(L) = T_r + (T_i-T_r)\exp(\frac{K}{Wc_p} L) \tag{D5}$$

Eliminating T_r from (D4) and (D5) gives

$$T_m = T_i\ B + T_o(1-B) \tag{D6}$$

where

$$B = (\frac{-1}{a} - \frac{E}{1-E})$$

and

$$a = \frac{KL}{Wc_p} \; ; \quad E = \exp(a)$$

If the heat transfer is directed from the tube wall to the flow (D6) holds with

$$B = \left(\frac{1}{a} - \frac{E}{1-E} \right)$$

$$a = \frac{KL}{Wc_p} \; ; \; E = \exp\,(-a)$$

Equation D6 also holds if the flow is in negative x direction.

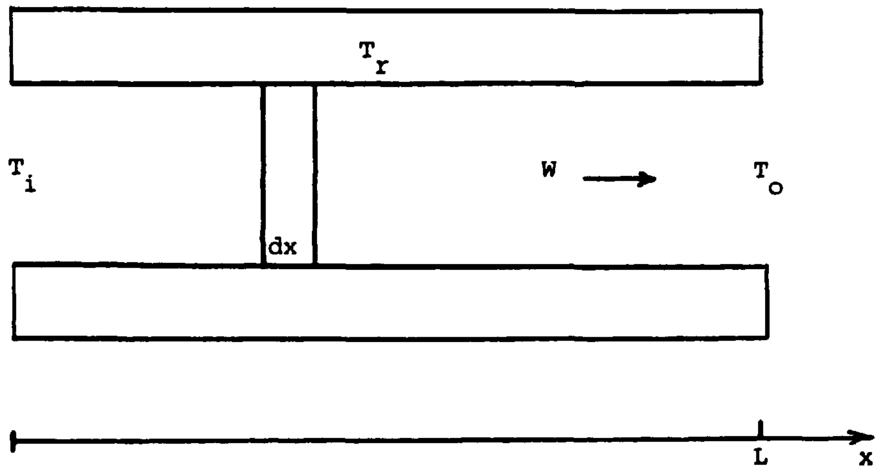

Fig. D. Mean temperature calculation.

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Title and author(s)	Date 1987-03-30
SIMULATION MODEL OF A PWR POWER PLANT Niels Larsen	Department or group: Energy Technology
	Groups own registration number(s)
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Abstract (Max. 2000 char.)

A simulation model of a hypothetical PWR power plant is described. A large number of disturbances and failures in plant function can be simulated. The model is written as seven modules to the modular simulation system for continuous processes DYSIM and serves also as a user example of this system. The model runs in Fortran 77 on the IBM-PC-AT.

Descriptors - INIS:

COMPUTERIZED SIMULATION; D CODES; FAILURES; FEEDWATER; NUCLEAR POWER PLANTS; PRESSURIZERS; PWR POWER REACTORS; SYSTEM ANALYSIS; TURBINES.

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